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A NONARBITARARY FATIGUE CRACK SIZE CONCEPT TO PREDICT TOTAL FATIGUE LIVES

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A method combining strain cycle fatigue and fracture mechanics concepts to predict a nonarbitrary crack initiation size, a_i, is presented. The nonarbitrary crack size is used as a demarcation between fatigue crack initiation and propagation methods of anlysis. Geometry, mean stress, and stress range all influence the value of a_i. Five different geometries were analyzed and tested at various load levels and two load ratios. Constant amplitude loading and initial incremental overload are considered. Specimens of an aluminum alloy, Al 7075-T651, were tested in the as-machined condition. Correlations

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between the analytical life predictions and experimental values of life fell within a factor of two in most cases.

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PREFACE

This report presents the results of an investigation performed in the Materials Engineering Research Laboratory at the University of Illinois. The principal investigator was Dr. Jo Dean Morrow with associate investigators D.F. Socie and Peter Kurath. The program was administered by the Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio under Project 2307, "Flight Vehicle Dynamics," Task 2307N1, "Research on the Behavior of Metallic and Composite Components of Airframe Structures." Financial support for this work was provided by the Air Force Office of Scientific Research under grant AFOSR 77-3195. Mr. Robert M. Engle (AFFDL/FBE) was the Air Force project engineer.

The research was conducted from February 1977 through July 1979.

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LIST OF SYMBOLS

a	Half crack length
a^*	Material constant
a_i, a_f	initial and final crack size
b, c	Fatigue strength and ductility exponents
$2B$, $2C$	Notch height and width
C', C''	Paris and Forman crack growth coefficient
D	Notch width
E	Elastic modulus
ΔK	Cyclic stress intensity
ΔK_c	Critical cyclic stress intensity
K_f	Fatigue notch factor
K_t	Theoretical elastic stress concentration factor
m, m'	Paris and Forman crack growth exponent
$2N_f$	Reversals to failure
N_i, N_p, N_t	Initiation life, propagation life, total life
r, ρ	Notch root radius
R	Load ratio , minimum load/maximum load
ΔS	Nominal stress amplitude
ΔS_x	Elastic stress at a given element
W	Width of plate
x	Distance from notch root
$\Delta\varepsilon/2$	Strain amplitude
ε_f', σ_f'	Fatigue ductility and strength coefficients
σ_0	Mean stress

SECTION I

INTRODUCTION

1. Background

Fatigue life estimates for notched members have been the subject of research for a number of years. Early investigators measured the endurance limit of notched and unnotched specimens and concluded that, in fatigue, notches have less of an effect than that predicted by the theoretical stress concentration factor, K_t. As a result, a fatigue notch factor, K_f, was introduced as an effective stress concentration factor in fatigue. A number of empirical relationships betwee K_f, K_t and notch size have been proposed (1,2). Topper et al. (3) extended this work to include the finite life region by employing Neuber's rule (4) to calculate elastic and plastic strains at the notch root. The appropriate value of K_f that should be employed in life prediction procedures was found to depend on material, load level, load history and the definition of failure (specimen separation or a crack of some arbitrary length) (5). The methods have been extended to estimate the life under variable amplitude load histories (6,7).

Use of these methods is termed a crack initiation analysis, because they estimate the number of cycles to initiate a crack of engineering significance. The crack propagation portion of the life is ignored in these methods, although it does influence the precise value of K_f employed. The relative fraction of the total fatigue life spent in propagating a crack is assumed to be small. In many cases this assumption is not justified (8). Nevertheless, these procedures have found widespread industrial application.

Since Paris (9) showed that the fatigue crack growth rate is a function of the cyclic stress intensity, several investigators have shown how to apply

fracture mechanics concepts to estimate the crack propagation life of notched structures subjected to variable amplitude load histories (10-12). These methods integrate the crack growth rate from an initial crack size to some critical crack size to obtain the crack propagation life. Crack initiation and early crack growth stages of the total fatigue life are ignored.

As a result, these methods are limited to problems that have pre-existing fatigue crack flaws. In an effort to estimate the total fatigue life of fastener holes, Potter (13) postulated an equivalent initial flaw size. It is determined by calculating the initial flaw size that would be required to give the total fatigue life of a laboratory specimen if the crack growth rate was integrated. The equivalent initial flaw size is not a constant, since it depends on the material, notch size, load level and loading history. As a result, the concept cannot be applied to different components or load histories without experimental data. El Hadad et al. (14) proposed a model to explain the growth of short cracks by introducing an intrinsic defect size that is constant for a given material. It is determined from the smooth specimen endurance limit and threshold stress intensity factor.

Recently, several investigators have calculated the total fatigue life by employing both crack initiation and crack propagation concepts. Initial crack sizes for the propagation analysis are assumed to be between 10^{-5} in. and 10^{-1} in. In the discussion of their work, Nelson and Fuchs (11) postulated that the fatigue damage, due to crack initiation of an arbitrary element, located along the potential crack path, decreases as the distance from the notch root increases. Fatigue damage, due to propagation, increases as the distance from the notch root increases. The intersection of the two

damage curves may be considered as the demarcation between crack initiation and propagation. Methods for calculating the damage due to each mechanism were not described. Smith and Miller (15) proposed that the crack growth near the notch is a function of the plastic strain range and also decreases as the distance from the notch root increases. The crack growth rate, as a function of the cyclic stress intensity, increases as the distance from the notch root increases. The two rates intersect at some distance from the notch root. Later, Hammouda and Miller (16) proposed that the growth rate of cracks near the notch should be described by elastic-plastic fracture mechanics concepts. Crack growth is determined by the interaction of plastic zone at the crack tip and the plastic zone near the notch.

Based on the elastic stress intensity solution for a small crack growing in the notch stress field, Dowling (17) suggests that a crack is initiated when it reaches a length equal to 20 percent of the notch root radius. Strain cycle fatigue concepts are employed to calculate the initiation life and linear elastic fracture mechanics methods are used to determine the propagation life. He provided a computational method and experimental data for 4340 steel with two notch geometries. Socie et al. (18) proposed a model for determining a nonarbitrary transition crack size by assuming that strain cycle fatigue mechanisms control the initial crack development until the crack propagation rate exceeds the crack initiation rate of elements along the potential crack path.

2. Purpose and Scope

The goal of this program was to utilize the concept of a nonarbitrary fatigue crack size in a working computer algorithm for predicting total fatigue lives. A test program employing various notches in plate specimens was performed to determine the viability of the concept.

SECTION II
ANALYSIS

1. Basic Concepts

Low cycle fatigue formulations have been successfully used to estimate crack initiation lives of notched members (6-8). Basically, if the local stresses and strains are known, initiation life can be related to fatigue data obtained from smooth laboratory specimens. Fatigue resistance of metals is usually characterized by a cyclic strain-life curve. Smooth specimens tested to failure under fully-reversed constant amplitude strain control provide these curves. The relation between strain amplitude and reversals to failure is usually represented in the following form:

$$\frac{\Delta\varepsilon}{2} = \varepsilon_f' (2N_f)^c + \frac{\sigma_f'}{E} (2N_f)^b \qquad (1)$$

To account for the presence of a mean stress, the strain-life equation may be modified to the following form:

$$\frac{\Delta\varepsilon}{2} = \varepsilon_f'(2N_f)^c + \frac{(\sigma_f' - \sigma_0)}{E} (2N_f)^b \qquad (2)$$

Fatigue crack propagation under constant amplitude loading is most frequently represented in the form proposed by Paris (9).

$$\frac{da}{dN} = C'(\Delta K)^m \qquad (3)$$

There have been numerous modifications of this basic form (19-21) to account for mean load, sequence, and crack closure effects. Final crack sizes are determined from fracture mechanics concepts and the appropriate fracture toughness data. Propagation lives can be calculated by integrating Eq. 3,

$$N_p = \int_{a_i}^{a_f} \frac{da}{C'(\Delta K)^m} \qquad (4)$$

Initial crack sizes, a_i, assumed in the literature, range from approximately 10^{-5} to 10^{-1} inches. This range in a_i can affect the calculated propagation lives by orders of magnitude. Also, the assumed value of a_i may influence the total fatigue life estimates in a similar manner.

In this research, crack initiation life was represented in terms of low cycle fatigue concepts as described in Appendix B, while using a Forman (22) description of crack propagation:

$$\frac{da}{dN} = \frac{C'' \Delta K^{m'}}{(1 - R)K_c - \Delta K} \qquad (5)$$

Equation 5 accounts for mean load effects in terms of the ratio of minimum to maximum load, R. Propagation, as described by Forman, is in terms of a cyclic rate of damage criterion, while strain cycle fatigue data are generally presented as total cycles to failure. To change these two models (Eqs. 2 and 5) into comparable forms, the low cycle fatigue life data are converted to a rate of initiation damage. It is assumed that for some number of cycles the initiation rate dominates, while propagation behavior controls during the later portion of fatigue life. A nonarbitrary crack initiation length, a_i, is defined to be the point where the two rates reach the same value. This method of determining a_i will be referred to as the intersecting rate analysis. Another equally valid approach to defining a_i, which will be referred to as the minimum life estimate, is to predict the total life from initiation and propagation models as before for various

values of x in Fig. 1. At some distance from the notch the calculated total life will be a minimum, and this value defines a_i.

2. Details of Implementation

Imagine a series of microfatigue elements ahead of a notch root (Fig. 1a), considering them to simulate smooth fatigue specimens. From the stress and strain distributions (Fig. 1b, 1c) for the notched plate obtained by using a finite element analysis, or mathematical formulation for a finite width notched plate, one can assign cyclic stresses and strains to the various elements. Finite element methods applied to this problem are discussed in (23). Finite width plate mathematical formulations involve elastic stresses and strains, whereas most problems at notches involve some degree of plasticity.

It is possible, given the nominal stresses and local elastic stresses and strains, to estimate the elasto-plastic stresses and strains using Neuber's rule (4) as follows:

$$\frac{(\Delta S_x)^2}{4E} = \frac{\Delta\sigma}{2}\frac{\Delta\varepsilon}{2} \tag{6}$$

The value of ΔS_x defines the local elastic stress range for a given element a distance x from the notch root. Combining this information with Hook's law for elastic strains and a power law for plastic strains,

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \tag{7}$$

results in the following relation.

$$\frac{(\Delta S_x)^2}{4E} = \frac{\Delta\sigma^2}{4E} + \frac{\Delta\sigma}{2}\left(\frac{\Delta\sigma}{2K'}\right)^{1/n'}$$

This equation can be solved rather easily by iterative procedures using a computer. Smooth specimen fatigue lives are then assigned to the various elements

as described in Appendix B (Fig. 1d). It is then possible to construct a curve with the dimensions of life versus position on the x axis (Fig. 1e) For the minimum life prodecure, the initiation life is defined as the value of the fatigue life of the element at the position $x = a_i$. The reciprocal of the derivative of the life with respect to x can be calculated by numerical methods at various points along the x axis resulting in dx/dN_f versus distance from the notch root (Fig. 1f). In this way strain cycle data are converted to a rate form for the intersecting rate analysis.

Yet another method to procure an initiation life estimate is to use Neuber's rule in conjunction with Peterson's (24) relation.

$$K_f = 1 + \frac{K_t - 1}{1 + \frac{a^*}{r}} \tag{9}$$

This calculation was done merely for comparison with the previous two methods.

Similarly, crack propagation data are usually presented in the form of da/dN versus ΔK (Fig. 2a). From linear elastic fracture mechanics solutions of finite width cracked plates, one can determine ΔK versus x (Fig. 2b) being of the form:

$$\Delta K = \Delta S \sqrt{\pi a}\, F(\tfrac{a}{W})\, F(Q) \tag{10}$$

For a finite width center cracked plate, the correction factors have the form,

$$F(\tfrac{a}{W}) = \sqrt{\operatorname{Sec}\,(\tfrac{\pi a}{W})}; \qquad F(Q) = 1 \tag{11}$$

However, for small cracks growing out of notches, this is not a suitable representation due to the notch root plastic field. Emery's (25) solution can be used to represent this phenomenon and has been employed by Dowling (17).

Another method accounting for this, proposed by Miller and Smith (15), considers an equivalent crack length, yielding:

$$\Delta K = \Delta S\sqrt{\pi a}\sqrt{[1.0 + 7.69\sqrt{D/\rho}]} \tag{12}$$

with the provision that,

$$a < 0.13\sqrt{D\rho}$$

in other words, that the crack is small. Note that D is the notch width and ρ the notch root radius. This formulation was employed to estimate ΔK for small cracks. As the cracks grow out of the notch, linear elastic fracture mechanics was employed to estimate ΔK. With this information one can construct a curve with dimensions ΔK versus x. Combining ΔK versus x, and da/dN versus ΔK results in a curve with dimensions da/dN versus x (Fig. 2c).

For the intersecting rate analysis, the strain cycle fatigue data and crack growth data are in a comparable form. Utilizing these assumptions, initiation and propagation rates were calculated for each element and compared (Fig 3). When the propagation rate exceeds the initiation rate for a given element, the location of the previous element is designated a_i. Initiation life is defined as the fatigue life of the element at $x = a_i$. Knowing K_c from crack growth data, one may determine a_f, the final crack size. Integrating Eq. 5 from a_i to a_f provides an estimate of the propagation life. Combine the two for a total life estimate.

The minimum life analysis assumes various values of a_i. For each x, the initiation life is defined as before, and integration of Eq. 5 from that specific x to a_f, provides a propagation life estimate. Again these two are combined for a total life estimate, and the assumed x that results in the minimum total life is denoted as a_i.

3. Implications of the Assumptions

The use of Miller and Smith's formulation for small cracks in the formulation of ΔK includes the influence of geometry in the propagation model. Forman's equation incorporates load ratio, therefore mean load, into the calculation of da/dN. The differing stress and strain distributions result in the initiation length and life being a function of notch geometry. Local mean stress and strain range were used in the calculation of fatigue cycles to failure and, thus, were also included in the initiation concept. The material properties incorporated through the Forman propagation model and strain-life calculations allow the material to affect the results also. It is through these considerations that a_i becomes unique for a given material, nominal load range, load ratio, and geometry with respect to the initiation and propagation models employed.

SECTION III
EXPERIMENTAL PROGRAM

An aluminum alloy, 7075-T651, that was supplied by Alcoa was used in this investigation. All specimens were machined so that loading was in the rolled direction of the 0.25 inch thick plate.

Smooth fatigue specimens 0.200" in circular cross section with a gage length of 0.50 in were used to generate the baseline fatigue data. Some of these specimens were initially overstrained for ten cycles of $\pm 1\%$ followed by 25 cycles of linearly decreasing strains to zero. Side notched plate samples 2.0 in wide and 0.08 in thick were employed to obtain da/dN data at a load ratio of 0.1, while center notched specimens of similar dimensions were used at a load ratio of -1.0. An incremental polynomial data reduction program generated the Forman equation constants for both load ratios and the Paris constants at a load ratio of 0.1. The results are tabulated in Appendix A. All tests were conducted on closed loop electro-hydraulic test systems.

To compare with predicted values of life, center notched plate specimens with thickness of 0.08 in, width of 2.00 in, notch width of 0.5 in, and notch radii varying from 0.25 in to 0.015 in, were tested under constant cyclic load at R ratios of -1.0 and 0.1 (Figs. 4 and 5). Maximum nominal stress levels varied from 5 ksi to 30 ksi.

Optical observations were periodically made with a 40X traveling microscope to detect the first visible crack. Small cracks of the size of the predicted a_i values could not be observed due to microscope resolution. Further observations were made of crack growth on some specimens after sizable cracks had developed to ensure that they followed the trends predicted from the crack growth data.

Finally some tests at R = -1.0 using specimens of similar dimensions were incrementally overloaded at the start of the test to avoid mean residual stress effects. They were then cycled to failure at constant amplitude. Total lives for complete separation of all specimens are tabulated in Tables 1 and 2.

SECTION IV
DISCUSSION

Analytical predictions of life for constant amplitude loading using the intersecting rate method, the minimum life method, and Neuber analysis for the various geometries are presented in Tables 3 through 7. Total life for predicted and experimental results versus stress level for each geometry are graphically presented in Figs. 6 through 15 for the minimum life approach since the two methods of analysis give essentially the same results.

The value of $a^* = 0.02$ in., used in Peterson's relation, was obtained from the literature (26). The technique based on Neuber's rule does not give adequate life predictions, especially for sharp notches.

Table 8 and Figs. 16 and 17 present percentage of the total life that is due to initiation versus nominal stress level. Sharp notches and/or high loads cause the life to be propagation dominated, while the life for blunt notches and/or low loads tend to be mostly initiation dominated.

Table 9 lists calculated a_i values versus nominal stress level, and these results are presented in Figs. 18 and 19. Predicted values for a_i range between 10^{-4} to 10^{-2} in. The value of a_i exhibits a definite dependence on R ratio, load range and geometry. This indicates that one cannot arbitrarily assign a constant initiation crack size for a given material or geometry.

It should also be noted that a small value of a_i does not infer a short or a long initiation life. Rather it indicates a transition in mode of analysis is necessary. Local strain gradient, mean stresses, nominal stresses, and material all combine to dictate the a_i value. It can be noted that blunter notches and lower load levels tend to give smaller initial crack sizes for

either load ratio. Since the method of calculating the notch strain distribution to determine initiation life assumes that no crack is present, it is reassuring that the calculated a_i values are small, and the assumption that the notch strain field dominates at small crack sizes is reasonably valid.

A major point of controversy has been the definition of fatigue crack initiation and propagation. These terms have been used rather loosely and could have varied implications. When used in this report, initiation does not imply that there are no cracks or flaws present. Also the presence of small cracks does not infer that a da/dN versus ΔK type description is valid. Rather it is probably better to consider that there are two types of data commonly available to describe cyclic damage; smooth specimen, reduced to cyclic strain versus life data, and cracked plate, resulting in da/dN versus ΔK curves. A notched member fits neither of these two during its entire life. Portions of the total life may be adequately described by one or the other depending on load ratio, load range, notch acuity, and previous fatigue damage. It is also unclear whether a crack of size a_i actually exists after the number of cycles referred to as N_i. At present, it is probably best to regard a_i as a conceptual crack that quantitatively reflects a transition from smooth specimen damage description to a propagation or cracked plate damage criterion in a notched member subject to cyclic loading.

Initial incremental overloaded tests were conducted under the assumption that the initiation life predictions would be more affected than propagation dominated predictions. Table 10 lists and Fig. 20 illustrates the relationship between the percentage of the life due to initiation and the percentage

reduction in life due to an initial overloading. In general, it seems that those cases with a large percentage of initiation life were affected more by the overload than those with smaller percentages of calculated initiation life.

Finally, in Fig. 21 the results of analytical predictions versus experimental life are presented. For the most part between lives of 10^3 to 10^6 cycles the data fall within a factor of two of the predictions. Considering the range of notch acuity, load ratio, and load range, this seems encouraging.

SECTION V
CONCLUSION

The correlation between the predicted and actual lives for the notched members tested indicates that the concept of a nonarbitrary fatigue crack size is a viable technique for predicting total fatigue lives in notched members. The concept of a_i provides a demarcation between smooth specimen and cracked specimen types of damage evaluation. Many variables, including geometry, material, and loading conditions influence the value of a_i, so that the technique may be applicable to a broad range of problems. This approach seems more reasonable than assuming a constant value for initiated crack size. For the intermediate cases where the life is approximately half initiation and half propagation, an accurate value of a_i is necessary to obtain a reasonable estimate of the combined total life.

Another advantage to this method is that the need to determine K_f, which is used in most techniques for smooth specimen simulation of notched members, is eliminated. The fatigue notch factor, K_f, requires extensive fatigue testing of smooth and notched members. It should be noted that, perhaps, a_i concepts could be applied to infer approximate values of K_f and a^* without resorting to notched specimen testing.

Although no variable loading cases, other than initial overload, have been treated, it seems reasonable to extend the a_i concept to predict life under block type loading. Using constant amplitude smooth specimen data and cracked plate data, initiation damage/block as a function of x in Fig. 1 could be calculated using rainflow counting, Miner's rule, etc. In a manner similar to that followed by Socie (12), the crack advance/block as a function of x in Fig. 1 could also be estimated. One could then determine and a_i value and the corresponding number of "initiation blocks" and "propagation blocks."

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APPENDIX A

BASELINE MATERIAL PROPERTIES

FOR

Al 7075-T651

MECHANICAL PROPERTIES OF Al 7075-T651

<u>Monotonic Properties</u>			
Elastic Modulus	E	10×10^3 ksi	(68750 MPa)
Yield Strength, 0.2% Offset	S_y	77.9 ksi	(537 MPa)
Tensile Strength	S_u	85.4 ksi	(589 MPa)
True Fracture Strength	σ_f	95.1 ksi	(656 MPa)
Strength Coefficient	K	87.3 ksi	(602 MPa)
Percent Reduction in Area	%RA	13.5%	
True Fracture Ductility	ε_f	0.1451	
Strain Hardening Exponent	n	0.017	
<u>Cyclic Properties</u>			
Fatigue Ductility Coefficient	ε_f'	0.158	
Fatigue Ductility Exponent	c*	-0.83	
Fatigue Strength Coefficient	σ_f'	114.8 ksi	(792 MPa)
Fatigue Strength Exponent	b	-0.04	
Cyclic Yield Strength, 0.2% Offset	S_y'	78.5 ksi	(541 MPa)
Cyclic Strength Coefficient	K'	100.7 ksi	(694 MPa)
Cyclic Strain Hardening Exponent	n'	0.048	
<u>Propagation Properties</u>			
Paris Crack Growth Coefficient	C'	1.18×10^{-7}	
Forman Crack Growth Coefficient	C''	1.01×10^{-5}	
Paris Crack Growth Exponent	m	2.94	
Forman Crack Growth Exponent	m'	2.36	
Fracture Toughness	K_c	40 ksi$\sqrt{\text{in}}$	(43.9 MPa$\sqrt{\text{m}}$)

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* Indicates slope for high levels of plasticity

CONSTANT AMPLITUDE FATIGUE TEST RESULTS ON SMOOTH SPECIMENS

Material: Al 7075-T651 tested in rolled direction
(Strain control unless otherwise noted.)

Specimen No.	Strain Amplitude $\Delta\varepsilon/2$	Fatigue Life Reversals	STABLE or HALF-LIFE VALUES		
			Stress Amplitude $\Delta\sigma/2$, ksi (MPa)	Plastic Strain Amplitude $\Delta\varepsilon_p/2$	Modulus of Elasticity E, ksi (MPa)
1A	0.010	590	78.3 (540)	0.00217	10,000 (69,400)
6	0.010	566	78.5 (541)	0.00224	10,000 (69,600)
1	0.010	508	78.8 (543)	0.000213	10,000 (69,100)
11	0.0075	2,874	72.9 (503)	0.000312	10,100 (70,000)
12	0.0075	2,900	73.6 (507)	0.000297	10,200 (70,500)
2*	0.0075	1.964	74.7 (515)	0.000309	10,400 (71,700)
13	0.005	37,300** 37,600**	50.8 (350)	---	0,100 (70,000)
2A	0.005	36,300** 37,600**	48.8 (337)	---	9,760 (67,300)
7	0.005	36,300** 36,600**	51.6 (356)	---	10,300 (71,200)
15	0.004	106,100	40.4 (279)	---	10,100 (61,600)
10	0.004	97,300** 106,900	40.8 (281)	---	10,210 (70,400)
22	0.004	120,400** 124,800	41.8 (288)	---	10,400 (72,000)
65	0.0034	833,000	34.7 (239)	---	10,200 (70,100)
63	0.0034	905,000	35.1 (242)	---	10,200 (70,100)
*** 59	0.0029	2,499,000	28.5 (197)	---	9,800 (67,8000
*** 53	0.0029	3,002,000	29.2 (201)		10,100 (69,600)

*Failed by knife edge of strain gage.

**Ten percent load drop in strain controlled tests when recorded

***Load controlled tests

OVERSTRAIN* FATIGUE DATA ON SMOOTH SPECIMENS

Material: Al 7075-T651 tested in rolled direction

Specimen No.	Strain Amplitude $\Delta\epsilon/2$	Fatigue Life Reversals	STABLE or HALF-LIFE VALUES Stress Amplitude $\Delta\sigma/2$,ksi(MPa)	Plastic Strain Amplitude $\Delta\epsilon_p/2$	Modulus of Elasticity E,ksi(MPa)
89	0.0049	30,900	50.1 (345)	---	10,300 (70,800)
56	0.0049	29,300	50.1 (345)	---	10,300 (70,800)
55	0.0049	17,000	50.2 (346)	---	10,200 (70,300)
51	0.0039	81,100	40.1 (276)	---	10,200 (70,100)
71	0.0039	77,400	39.8 (247)	---	10,200 (70,300)
58	0.0039	76,100	39.7 (274)	---	10,200 (70,100)
57	0.0029	213,000	29.7 (205)	---	10,200 (70,100)
53	0.0029	217,300	29.7 (205)	---	10,200 (70,500)
66	0.0029	316,000	29.7 (205)	---	10,100 (69,800)

*Initially overstrained 10 cycles at +0.01 followed by 25 cycles of linearly decreased strain to zero.

APPENDIX 2
LOW CYCLE FATIGUE CONCEPTS

The most common form of the strain-life relation expressed in Eq. 1 is commonly applicable to most steels. The term, $\sigma_f/E(2N_f)^b$, represents the elastic strain amplitude and $\varepsilon_f'(2N_f)^c$ the plastic strain amplitude. On log-log coordinates of life versus strain amplitude, the elastic and plastic strain amplitudes have a linear relation with life and the exponents b and c are the slopes. When plotting the strain-life data for Al 7075-T651 in a similar fashion, it was observed that the log-log linear behavior occured within certain bounds of life, not the entire life range. Plastic strain amplitudes were negligible at lives greater than about 1000 cycles.

For computational purposes it was decided to fit an equation of the form

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f^*}{E}(2N_f)^{b'} + \frac{\varepsilon_f^*}{E}(2N_f)^{c'}$$

in short life region where plastic behavior was appreciable. The values of σ_f^* and ε_f^* are the intersection of the $\Delta\varepsilon/2$ axis at a life of one reversal for the linear relations in this region.

In the long life region it was found that a single Basquin type relation was sufficient.

$$\frac{\sigma_a}{E} = \frac{\sigma_f^{**}}{E}(2N_f)^{b''}$$

Again, σ_f^{**} obtained by extrapolating the linear relation in the long life region back to a life of one reversal. It should be noted $\sigma_f^* \neq \sigma_f^{**}$ and $b' \neq b''$.

To avoid any discontinuity, the equations were set equal to one another to find the life that satisfied both. This was close to 1000 cycles, and served as a demarcation between the two descriptions.

TABLE 1

CONSTANT AMPLITUDE EXPERIMENTAL RESULTS ON NOTCHED SPECIMENS OF Al 7075-T651, TOTAL LIFE

S_{max}(ksi)	Circular Notch r = 0.25 in	Slotted Notch r = 0.125 in	Elliptical Notch r = 0.062 in	Elliptical Notch r = 0.031 in	Elliptical Notch r = 0.015 in
R = -1.0					
5	---	---	5.00 E 6 (runout)	7.01 E 5	6.24 E 5
10	5.00 E 6 (runout)	1.23 E 6	1.10 E 5	3.69 E 4	3.07 E 4
15	8.83 E 4	4.65 E 4	1.10 E 4	8.30 E 3	7.62 E 3
20	1.18 E 3	5.58 E 3	2.39 E 3	2.07 E 3	---
R = 0.1					
5	---	---	---	---	5.00 E 6 (runout)
10	5.00 E 6 (runout)	4.20 E 6	1.13 E 6	1.41 E 5	7.12 E 4
15	4.76 E 5	5.50 E 4	3.60 E 4	2.00 E 4	1.55 E 4
20	4.52 E 4	2.16 E 4	9.65 E 3	9.76 E 3	4.88 E 3
25	1.77 E 4	1.18 E 4	5.00 E 3	3.88 E 3	2.22 E 3
30	9.70 E 3	4.38 E 3	2.94 E 3	1.89 E 3	---

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TABLE 2

INITIAL OVERSTRESS EXPERIMENTAL RESULTS ON NOTCHED SPECIMENS OF Al 7075-T651, TOTAL LIFE

S_{max}(ksi)	Circular Notch r = 0.25 in.	Slotted Notch r = 0.125 in	Elliptical Notch r = 0.062 in	Elliptical Notch r = 0.031 in	Elliptical Notch r = 0.015 in
R = -1.0; Nominal overstress = 30 ksi					
5	---	---	2.87 E 5	1.75 E 5	2.66 E 5
10	1.32 E 6	7.45 E 4	3.21 E 4	3.20 E 4	3.38 E 4
15	2.83 E 4	1.93 E 4	7.80 E 3	8.19 E 3	6.91 E 3
R = -1.0; Nominal overstress = 25 ksi					
5	---	5.00 E 6 (runout)	---	---	2.61 E 5
10	---	---	3.85 E 4	3.03 E 4	2.29 E 4
15	5.47 E 4	1.43 E 4	---	---	---

TABLE 3

CALCULATED RESULTS FOR CIRCULAR NOTCH, r = 0.25 in; Al 7075-T651

	Intersecting Rate Estimates				Minimum Life Estimates				Neuber
S_{max}(ksi)	a_i(in)	N_i	N_p	N_t	a_i(in)	N_i	N_p	N_t	N_t
R = -1.0									
5	3.70 E-4	1.17 E 8	2.73 E 5	1.17 E 8	3.70 E-4	1.17 E 8	2.73 E 5	1.17 E 8	2.36 E 8
10	1.20 E-4	8.16 E 5	1.35 E 5	9.50 E 5	4.90 E-4	8.36 E 5	3.68 E 4	8.73 E 5	1.67 E 6
15	6.00 E-4	4.65 E 4	1.01 E 4	5.66 E 4	1.11 E-3	4.81 E 4	7.02 E 3	5.51 E 4	9.24 E 4
20	1.70 E-3	6.41 E 3	2.33 E 3	8.74 E 3	2.04 E-3	6.55 E 3	2.16 E 3	8.71 E 3	1.18 E 4
25	3.55 E-3	1.47 E 3	7.72 E 2	2.24 E 3	3.62 E-3	1.47 E 3	7.64 E 2	2.24 E 3	2.52 E 3
30	4.97 E-3	4.32 E 2	3.03 E 2	7.35 E 2	4.99 E-3	4.33 E 2	3.01 E 2	7.35 E 2	3.94 E 2
R = 0.1									
10	4.60 E-4	1.36 E 8	1.15 E 5	1.36 E 8	4.60 E-4	1.36 E 8	1.15 E 5	1.36 E 8	2.89 E 8
15	2.10 E-4	5.34 E 6	7.17 E 4	5.41 E 6	2.10 E-4	5.34 E 6	7.17 E 4	5.41 E 6	1.20 E 7
20	1.20 E-4	4.83 E 5	4.97 E 4	5.33 E 5	3.60 E-4	4.92 E 5	1.76 E 4	5.10 E 5	1.13 E 6
25	3.10 E-4	6.97 E 4	8.93 E 5	7.87 E 4	5.90 E-4	7.13 E 4	5.63 E 3	7.69 E 4	1.70 E 5
30	7.90 E-4	1.35 E 4	2.42 E 3	1.60 E 4	9.50 E-4	1.38 E 4	2.20 E 3	1.60 E 4	4.16 E 4

TABLE 4

CALCULATED RESULTS FOR SLOTTED NOTCH, r = 0.125 in; Al 7075-T651

	Intersecting Rate Estimates				Minimum Life Estimates				Neuber
S_{max}(ksi)	a_i(in)	N_i	N_p	N_t	a_i(in)	N_i	N_p	N_t	N_t
R = -1.0									
5	2.70 E-4	2.07 E 7	2.64 E 5	2.10 E 7	2.70 E-4	2.07 E 7	2.64 E 5	2.10 E 7	7.89 E 7
10	2.20 E-4	1.46 E 5	5.28 E 4	1.99 E 5	6.70 E-4	1.54 E 5	2.30 E 4	1.78 E 5	5.58 E 5
15	1.00 E-3	8.90 E 3	5.79 E 3	1.47 E 4	1.50 E-3	9.48 E 3	4.90 E 3	1.44 E 4	3.08 E 4
20	2.57 E-3	1.39 E 3	1.57 E 3	2.95 E 3	2.80 E-3	1.43 E 3	1.52 E 3	2.94 E 3	4.00 E 3
25	4.63 E-3	3.58 E 2	5.30 E 2	8.88 E 2	4.76 E-3	3.62 E 2	5.24 E 2	8.87 E 2	5.53 E 2
30	4.97 E-3	1.41 E 2	2.14 E 2	3.55 E 2	4.99 E-3	1.14 E 2	2.14 E 2	3.55 E 2	1.09 E 2
R = 0.1									
10	3.40 E-4	2.03 E 7	1.09 E 5	2.04 E-7	3.40 E-4	2.03 E 7	1.09 E 5	2.04 E 7	8.87 E 7
15	1.50 E-4	7.11 E 5	7.11 E 4	7.82 E-5	2.90 E-4	7.26 E 5	3.86 E 4	7.65 E 7	3.43 E 6
20	2.40 E-4	5.86 E 4	1.77 E 4	7.64 E-4	5.80 E-4	6.19 E 4	9.11 E 3	7.11 E 4	3.08 E 5
25	3.12 E-3	9.52 E 2	1.84 E 3	2.79 E-3	3.17 E-3	9.64 E 2	1.8[illegible] E 3	2.79 E 4	5.10 E 4
30	4.97 E-3	2.46 E 2	6.40 E 2	8.86 E-2	4.99 E-3	2.46 E 2	6.39 E 2	8.85 E 2	1.52 E 4

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TABLE 5

CALCULATED RESULTS FOR ELLIPTICAL NOTCH, r=0.062 in; Al 7075-T651

	Intersecting Rate Estimates				Minimum Life Estimates				Neuber
S_{max}(ksi)	a_i(in)	N_i	N_p	N_t	a_i(in)	N_i	N_p	N_t	N_t
R = -1.0									
5	2.00 E-4	3.13 E 6	2.54 E 5	3.38 E 6	2.30 E-3	3.15 E 6	2.26 E 5	3.38 E 6	4.78 E 7
10	4.20 E-4	2.34 E 4	2.40 E 4	4.74 E 4	9.40 E-3	2.66 E 4	1.60 E 4	4.26 E 4	3.38 E 5
15	1.65 E-3	1.74 E 3	3.99 E 3	5.73 E 3	2.05 E-3	1.90 E 3	3.78 E 3	5.68 E 3	1.88 E 4
20	3.66 E-3	3.49 E 2	1.21 E 3	1.56 E 3	4.19 E-3	3.89 E 2	1.17 E 3	1.56 E 3	2.51 E 3
25	4.97 E-3	1.35 E 2	4.32 E 2	5.67 E 2	4.99 E-3	1.35 E 2	4.32 E 2	5.67 E 2	2.59 E 2
30	4.97 E-3	7.03 E 1	1.64 E 2	2.34 E 2	4.99 E-3	7.04 E 1	1.64 E 2	2.34 E 2	7.18 E 1
R = 0.1									
5	9.70 E-4	6.96 E 8	2.97 E 5	6.97 E 8	9.70 E-4	6.96 E 8	2.97 E 5	6.97 E 8	1.02 E 10
10	2.50 E-4	2.38 E 6	1.04 E 5	2.49 E 6	2.50 E-4	2.38 E 6	1.04 E 5	2.49 E 6	5.07 E 7
15	1.50 E-4	7.12 E 4	5.07 E 4	1.22 E 5	4.90 E-4	7.92 E 4	1.99 E 4	9.90 E 4	1.93 E 6
20	2.60 E-3	8.29 E 2	3.92 E 3	4.75 E 3	2.84 E-3	9.03 E 2	3.84 E 3	4.75 E 3	1.70 E 5
25	4.97 E-3	2.30 E 2	1.29 E 3	1.52 E 3	4.99 E-3	2.31 E 2	1.29 E 3	1.52 E 3	3.12 E 4

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TABLE 6

CALCULATED RESULTS FOR ELLIPTICAL NOTCH, r=0.03 in; Al 7075-T651

	Intersecting Rate Estimates				Minimum Life Estimates				Neuber
S_{max}(ksi)	a_i(in)	N_i	N_p	N_t	a_i(in)	N_i	N_p	N_t	N_t
R = -1.0									
5	1.40 E-4	4.13 E 5	2.57 E 5	6.69 E 5	3.50 E-4	4.57 E 5	1.33 E 5	5.89 E 5	4.58 E 7
10	7.90 E-4	3.97 E 3	1.47 E 4	1.86 E 4	1.30 E-3	5.01 E 3	1.28 E 4	1.78 E 4	3.24 E 5
15	2.30 E-3	4.21 E 2	3.33 E 3	3.75 E 3	2.59 E-3	4.73 E 2	3.27 E 3	3.74 E 3	1.79 E 4
20	4.48 E-3	1.60 E 2	1.07 E 3	1.23 E 3	4.45 E-3	1.58 E 2	1.07 E 3	1.23 E 3	2.42 E 3
25	4.47 E-3	7.58 E 1	3.88 E 2	4.64 E 2	4.99 E-3	7.60 E 1	3.88 E 2	4.64 E 2	2.45 E 2
R = 0.1									
5	7.00 E-4	8.45 E 7	2.89 E 5	8.48 E 7	7.00 E-4	8.45 E 7	2.89 E 5	8.48 E 7	9.78 E 9
10	1.80 E-4	2.17 E 5	1.02 E 5	3.20 E 5	3.10 E-4	2.35 E 5	6.87 E 4	3.03 E 5	4.83 E 7
15	1.54 E-3	9.90 E 2	1.07 E 4	1.17 E 4	1.55 E-3	9.99 E 2	1.07 E 4	1.17 E 4	1.83 E 6
20	4.47 E-3	2.97 E 2	3.18 E 3	3.48 E 3	4.48 E-3	2.98 E 2	3.18 E 3	3.48 E 3	1.62 E 5
25	4.97 E-3	1.07 E 2	1.16 E 3	1.26 E 3	4.90 E-3	1.07 E 2	1.15 E 3	1.27 E 3	3.01 E 4

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TABLE 7

CALCULATED RESULTS FOR ELLIPTICAL NOTCH, r=0.015 in; Al 7075-T651

	Intersecting Rate Estimates				Minimum Life Estimates				Neuber
S_{max} (ksi)	a_i (in)	N_i	N_p	N_t	a_i(in)	N_i	N_p	N_t	N_t
R = -1.0									
5	1.50 E-4	4.55 E 4	1.81 E 5	2.26 E 5	5.20 E-4	6.47 E 4	9.32 E 4	1.58 E 5	8.84 E 7
10	1.00 E-3	7.55 E 2	1.23 E 4	1.30 E 4	1.59 E-3	1.14 E 3	1.13 E 4	1.24 E 4	6.25 E 5
15	2.91 E-3	1.90 E 2	3.02 E 3	3.21 E 3	2.89 E-3	1.88 E 2	3.03 E 3	3.21 E 3	3.45 E 4
20	4.03 E-3	8.83 E 1	1.02 E 3	1.11 E 3	3.94 E-3	8.61 E 1	1.03 E 3	1.11 E 3	4.47 E 3
25	1.84 E-3	1.64 E 1	4.30 E 2	4.46 E 2	2.93 E-3	2.26 E 1	3.96 E 2	4.18 E 2	6.75 E 2
R = 0.1									
5	4.90 E-4	7.76 E 6	2.84 E 5	8.05 E 6	4.90 E-4	7.76 E 6	2.84 E 5	8.05 E 6	1.94 E 10
10	2.00 E-4	1.38 E 4	7.15 E 4	8.53 E 4	5.60 E-4	2.16 E 4	4.26 E 4	6.43 E 4	9.96 E 7
15	2.78 E-3	3.57 E 2	9.06 E 3	9.42 E 3	2.81 E-3	3.66 E 2	9.05 E 3	9.42 E 3	3.91 E 6
20	4.61 E-3	1.60 E 2	3.02 E 3	3.18 E 3	4.34 E-3	1.45 E 2	3.04 E 3	3.18 E 3	3.52 E 5
25	3.57 E-3	4.50 E 0	1.15 E 3	1.15 E 3	3.57 E-3	4.50 E 0	1.15 E 3	1.15 E 3	5.73 E 4

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TABLE 8

% INITIATION USING MINIMUM LIFE ESTIMATES: Al 7075-T651

S_{max}(ksi)	Circular Notch r = 0.25 in	Slotted Notch r = 0.125 in	Elliptical Notch r = 0.062 in	Elliptical Notch r = 0,031 in	Elliptical Notch r = 0.015 in
R = -1.0					
5	99.2	98.6	93.1	77.6	40.9
10	95.7	86.5	62.4	28.1	9.2
15	87.3	65.8	33.4	12.6	5.8
20	75.2	48.6	24.9	12.8	7.7
25	65.6	40.8	23.8	16.3	5.4
30	58.9	39.7	30.0	----	----
R = 0.1					
5	----	----	99.9	99.6	96.3
10	99.4	99.5	95.5	77.5	33.5
15	98.7	94.9	80.0	85.3	3.9
20	96.4	87.1	19.0	3.5	4.5
25	92.7	34.5	15.2	8.4	3.9
30	86.3	27.7	----	----	----

Note: % Initiation = (Calculated Initiation Life/Calculated Total Life) X 100

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TABLE 9

a_i(in) USING MINIMUM LIFE ESTIMATES; Al 7075-T651

S_{max}(ksi)	Circular Notch r = 0.25 in	Slotted Notch r = 0.125 in	Elliptical Notch r = o.062 in	Elliptical Notch r = 0.031	Elliptical Notch r = 0.015 in
R = -1.0					
5	3.70 E-4	2.70 E-4	2.30 E-3	3.50 E-4	5.20 E-4
10	4.90 E-4	6.70 E-4	9.40 E-3	1.30 E-3	1.59 E-3
15	1.11 E-3	1.50 E-3	2.05 E-3	2.59 E-3	2.89 E-3
20	2.04 E-3	2.80 E-3	4.19 E-3	4.45 E-3	3.94 E-3
25	3.63 E-3	4.76 E-3	4.99 E-3	4.99 E-3	2.93 E-3
30	4.99 E-3	4.99 E-3	4.99 E-3	---	---
R = 0.1					
5	---	---	9.70 E-4	7.00 E-4	4.90 E-4
10	4.60 E-4	3.40 E-4	2.50 E-4	3.10 E-4	5.60 E-4
15	2.10 E-4	2.90 E-4	4.90 E-4	1.55 E-3	2.81 E-3
20	3.6- E-4	5.30 E-3	2.84 E-3	4.48 E-3	4.34 E-3
25	5.90 E-4	3.17 E-3	4.99 E-3	4.90 E-3	3.57 E-3
30	9.50 E-4	4.99 E-3	---	---	---

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TABLE 10

CALCULATED % INITIATION-CONSTANT AMPLITUDE/% REDUCTION IN EXPERIMENTAL LIFE DUE TO OVERSTRESS

Al 7075-T651

S_{max} (ksi)	Circular Notch r = 0.25 in	Slotted Notch r = 0.125 in	Elliptical Notch r = 0.062 in	Elliptical Notch r = 0.031 in	Elliptical Notch r = 0.015 in
R = -1.0; Nominal overstress = 30 ksi					
5	99.2/---	98.6/---	93.1/94.3+	77.6/75.0	40.9/57.3
10	95.7/73.6+	86.5/93.9	62.4/70.8	28.1/13.2	9.2/-10.0
15	87.3/67.9	65.8/58.4	33.4/29.0	12.6/1.3	5.8/9.3
R = -1.0; Nominal overstress = 25 ksi					
5	99.2/---	98.6/16.0+	93.1/---	77.6/---	40.9/58.1
10	95.7/---	86.5/---	62.4/65.0	28.1/17.8	9.2/25.4
15	87.3/37.9	65.8/69.2	33.4/----	12.6/---	5.8/---

a) + sign after % reduction in life indicates one of the tests was a runout.

b) $\%\ \text{Reduction in Life} = \dfrac{\text{Constant Amplitude Life - Overstress Life}}{\text{Constant Amplitude Life}} \times 100$

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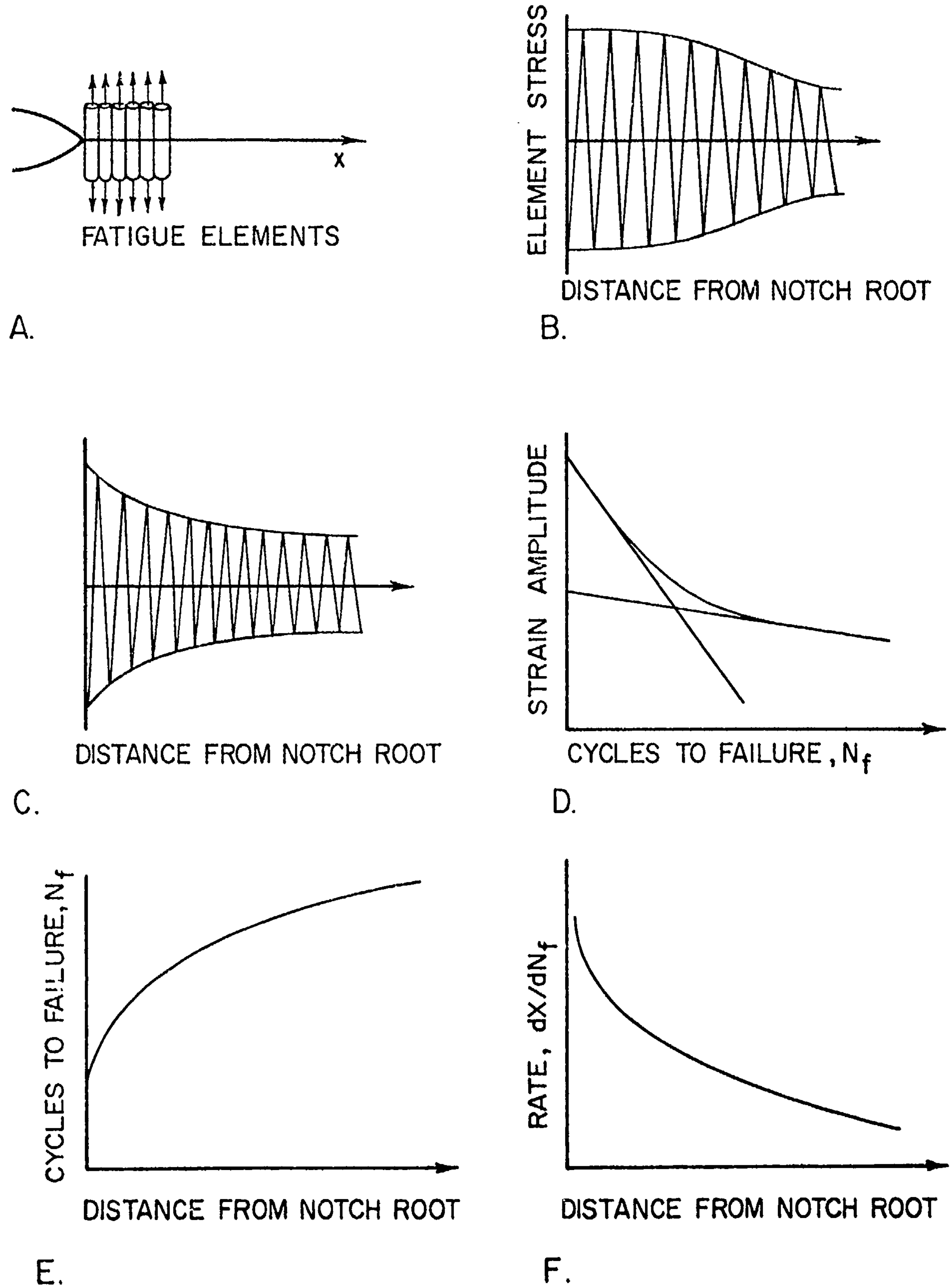


FIG. 1 SCHEMATIC ILLUSTRATION OF INITIATION CONCEPT

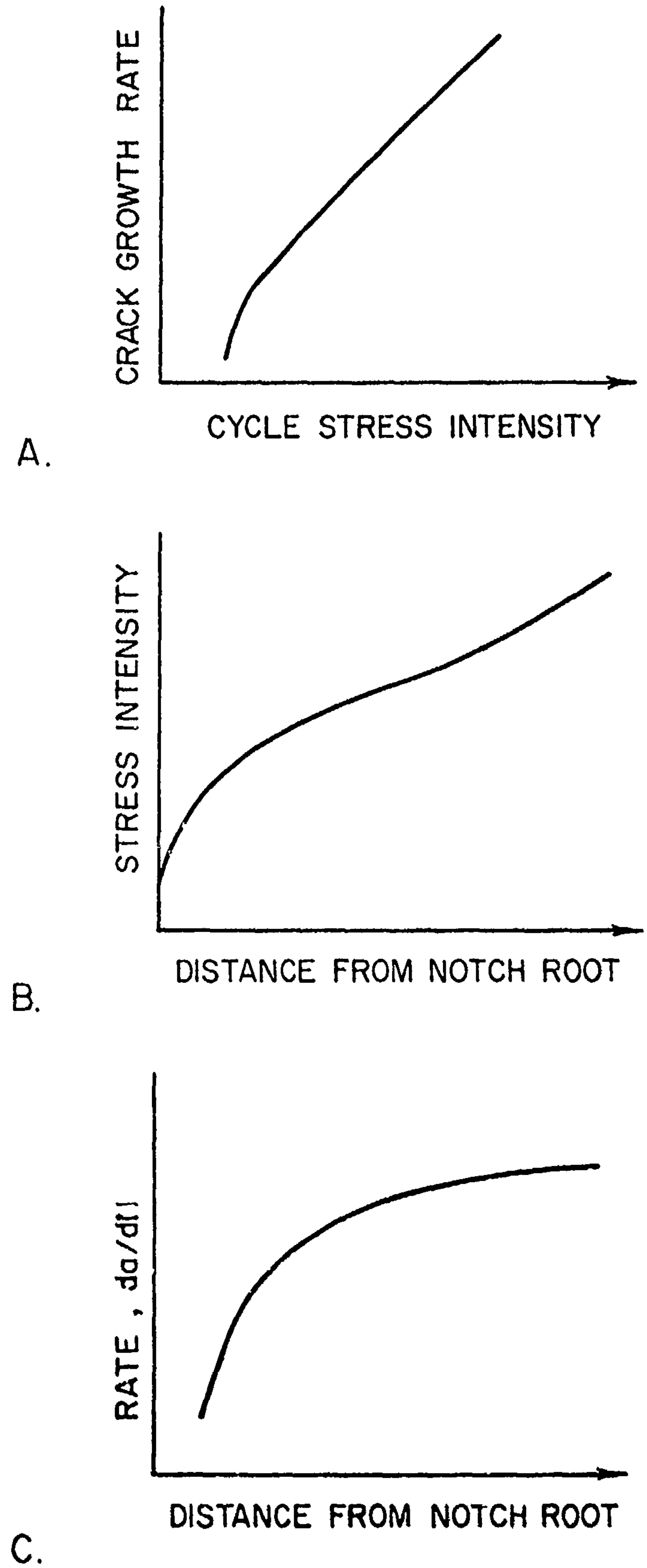


FIG. 2 SCHEMATIC ILLUSTRATION OF PROPAGATION CONCEPT

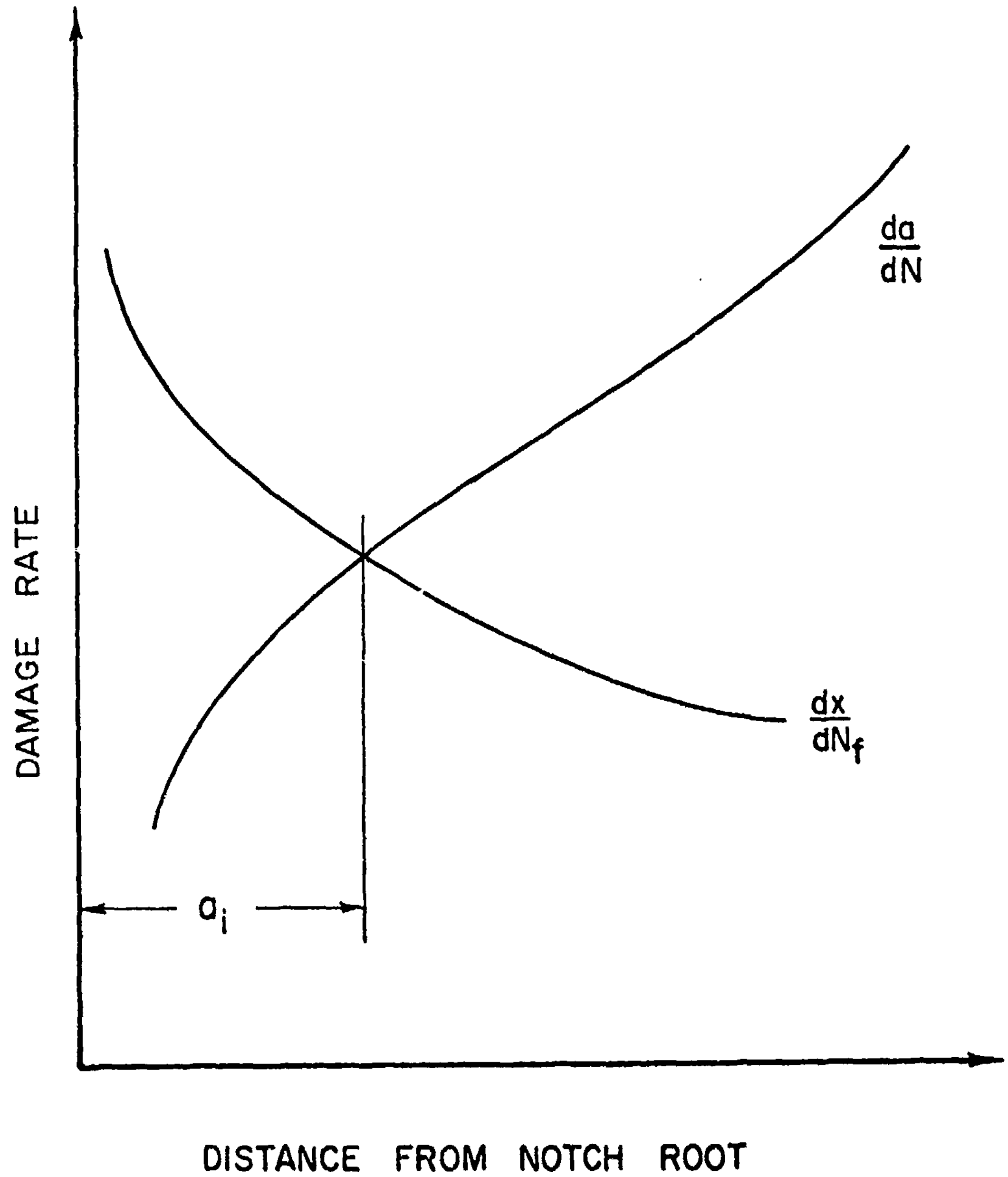
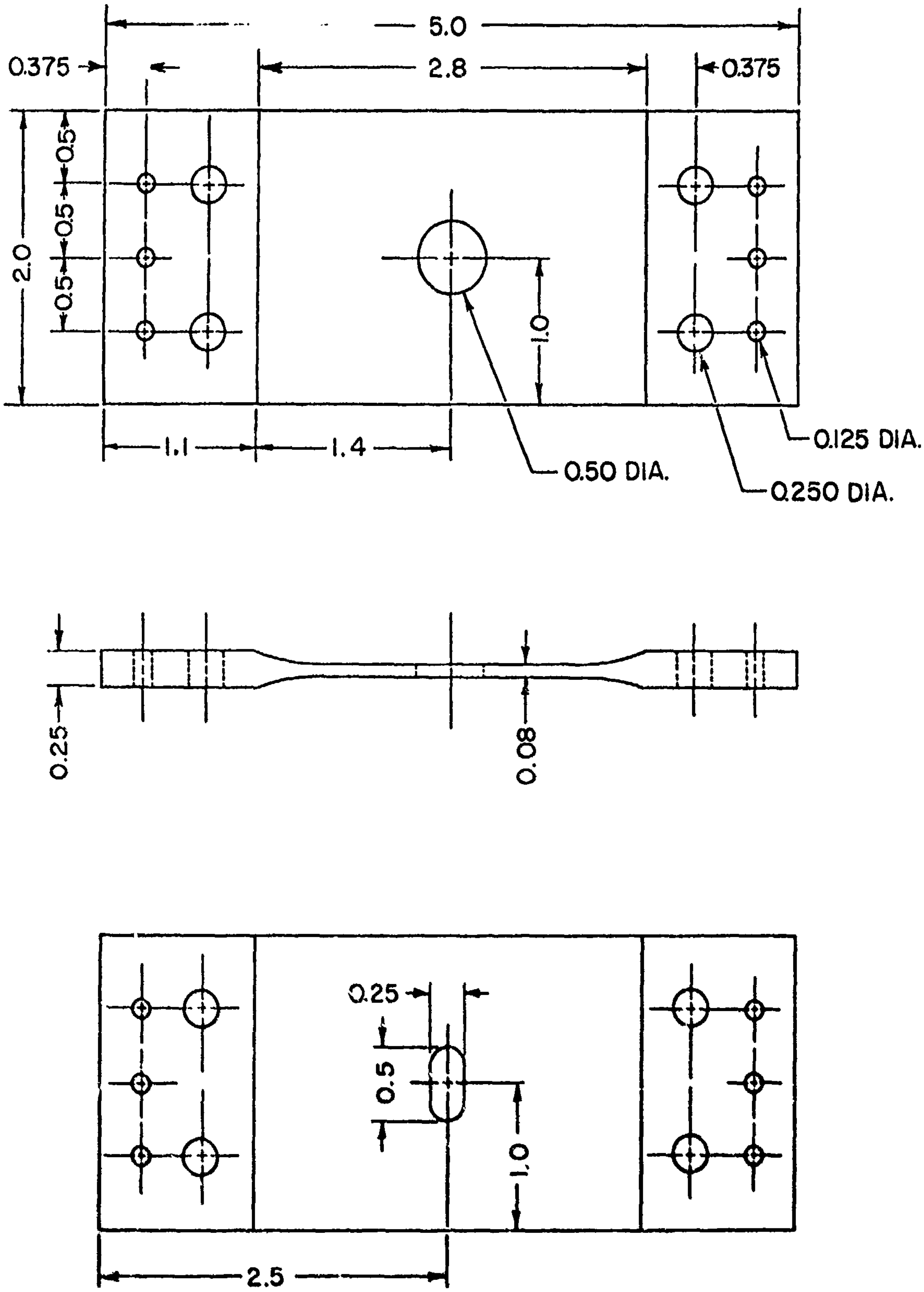
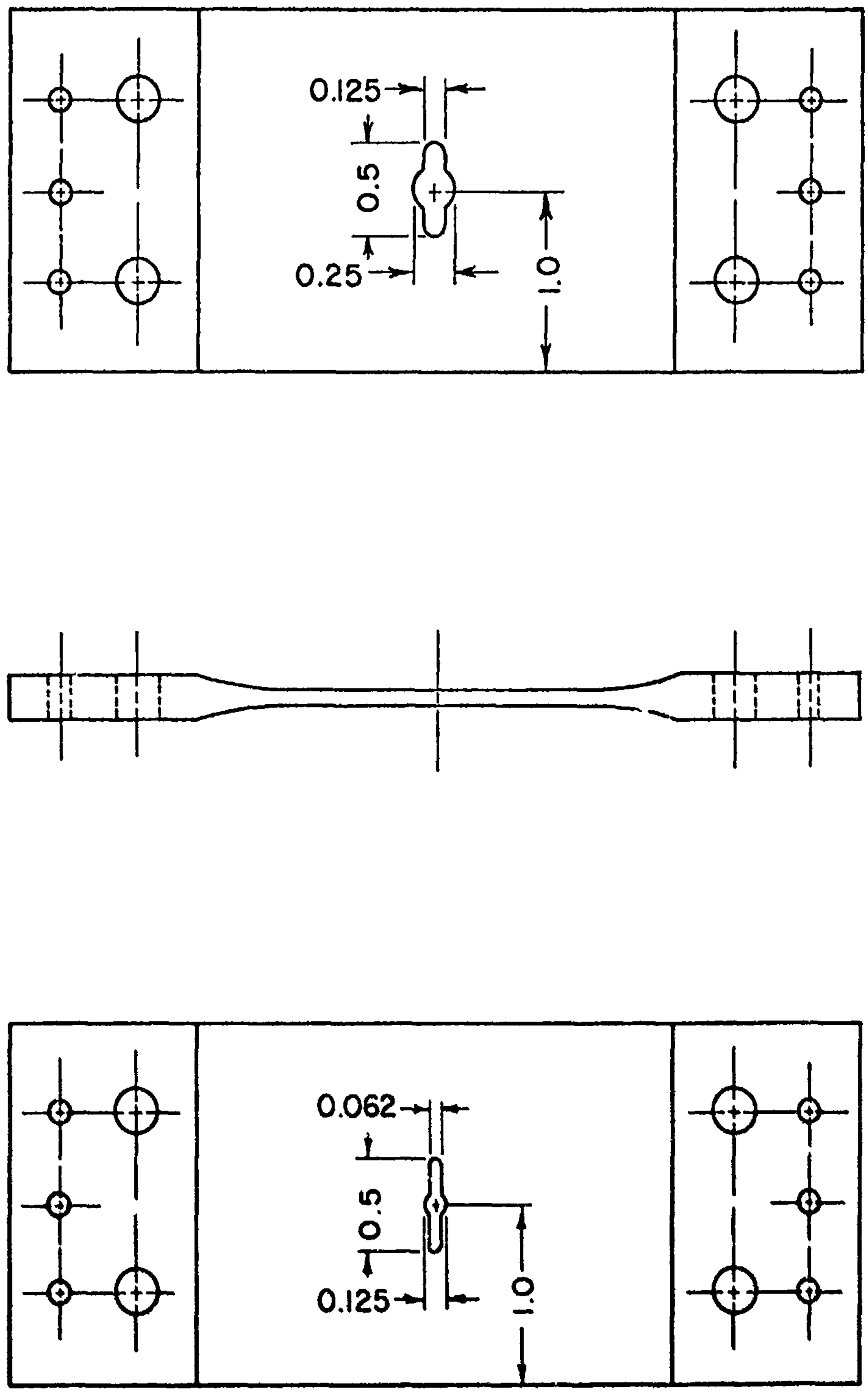


FIG. 3 SUPERPOSITION OF CRACK INITIATION AND PROPAGATION RATES



NOTE: ALL MEASUREMENTS IN INCHES

FIG. 4 SPECIMEN DIMENSIONS



NOTE: ALL MEASUREMENTS IN INCHES – OVERALL DIMENSIONS SAME AS FIG. 4

FIG. 5 SPECIMEN DIMENSIONS

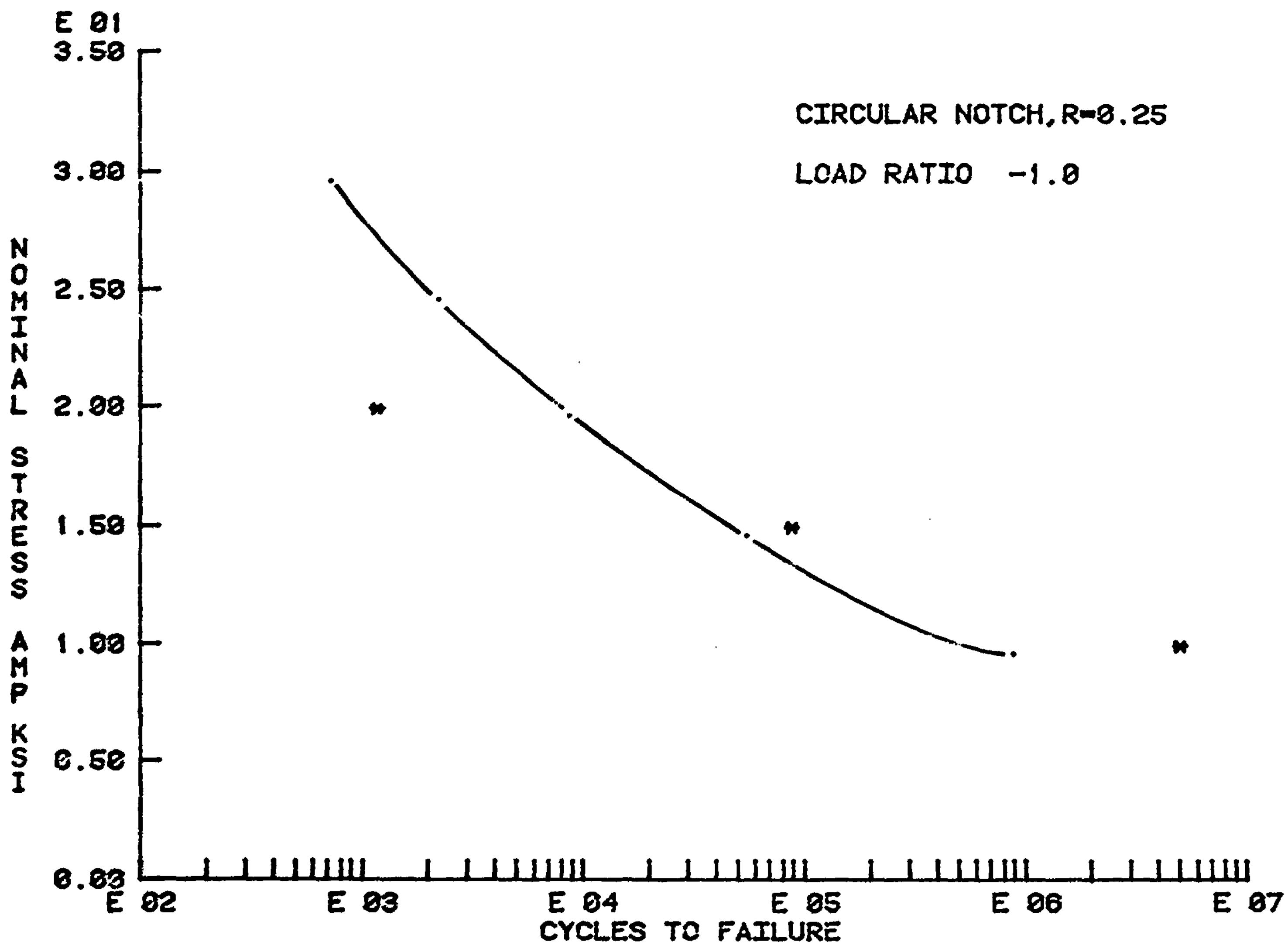


FIG. 6 ANALYTICAL AND EXPERIMENTAL RESULTS, R = -1.0, r = 0.25 IN

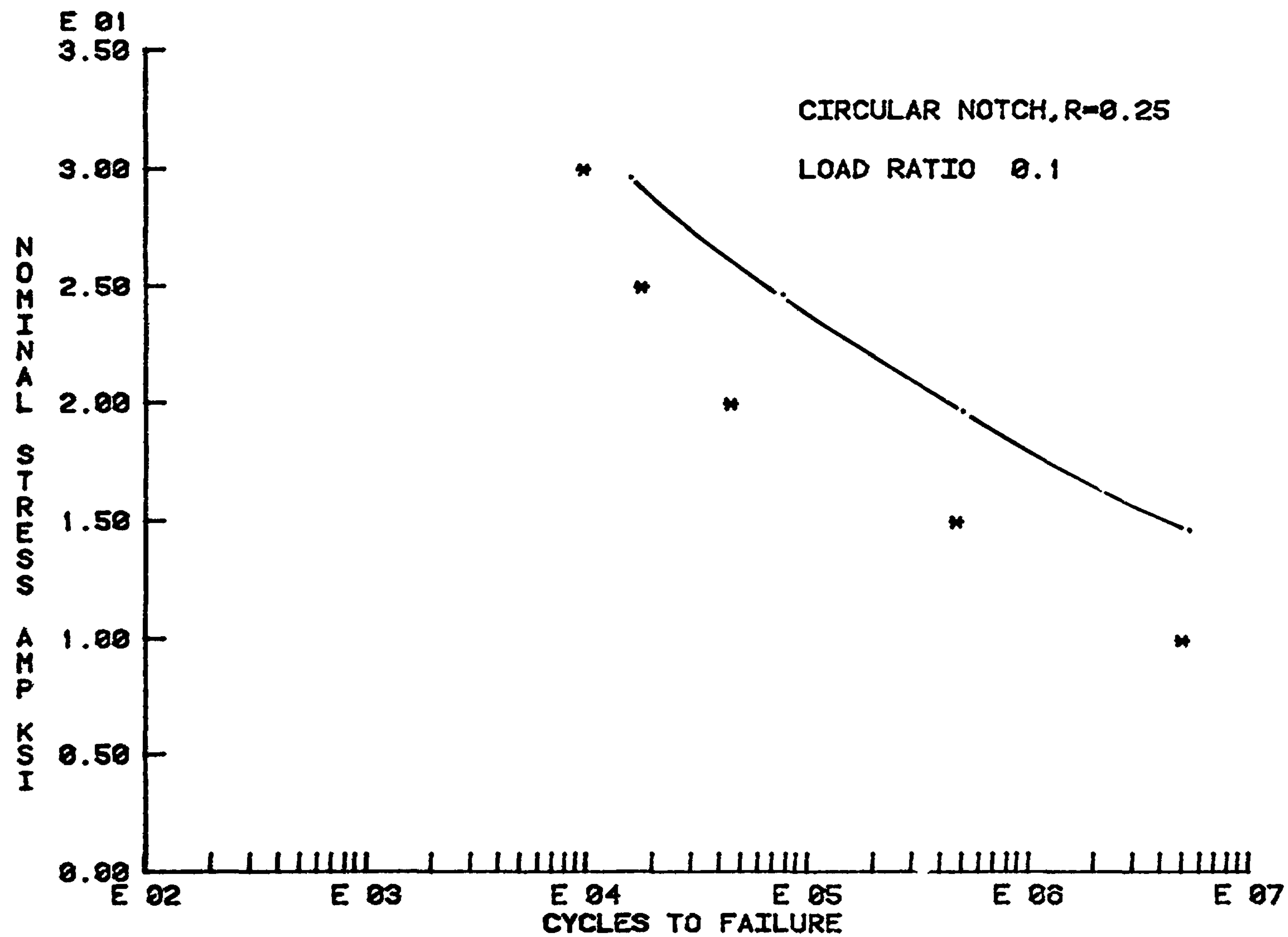


FIG. 7 ANALYTICAL AND EXPERIMENTAL RESULTS, R = 0.1, r = 0.25 IN

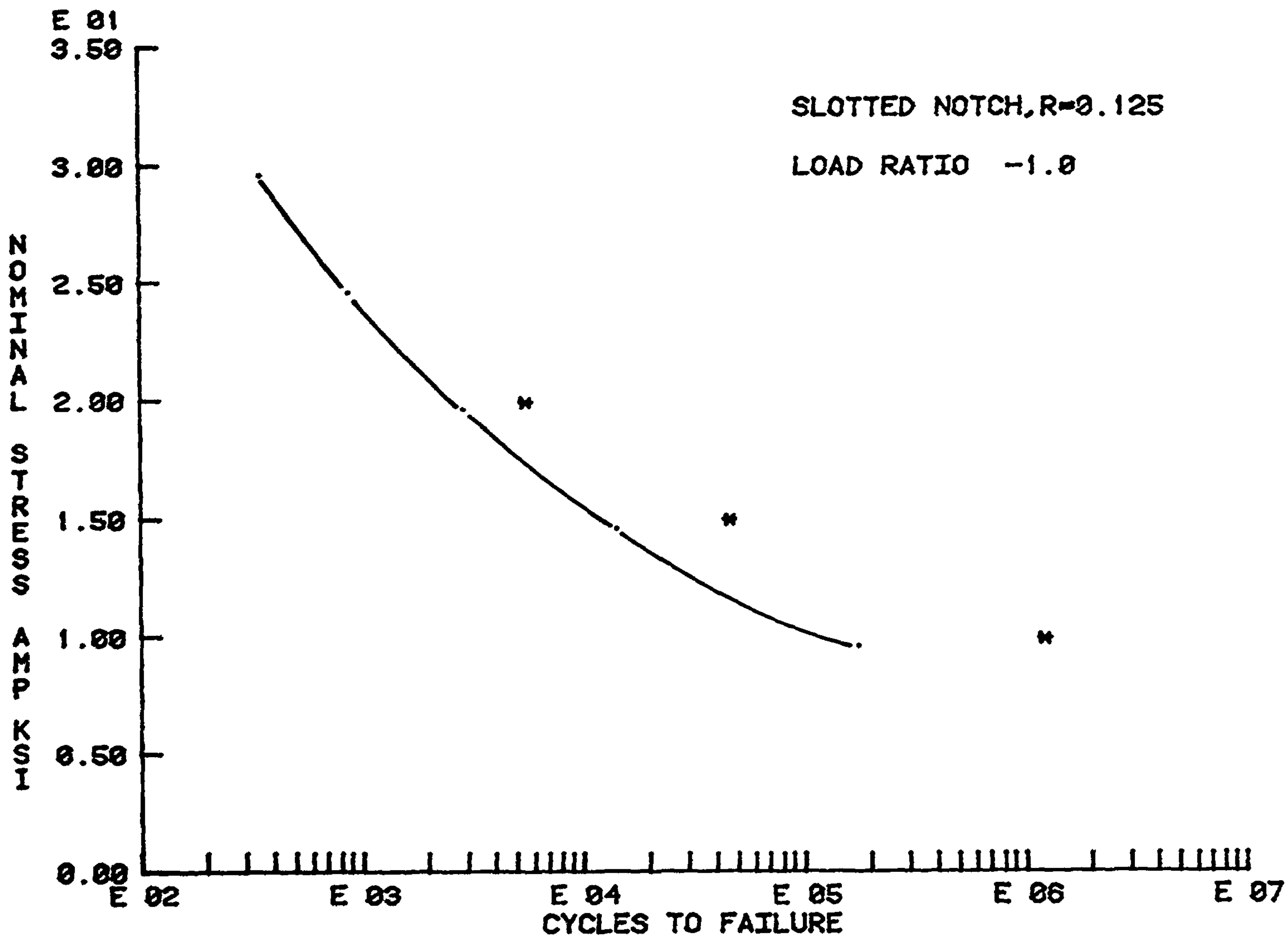


FIG. 8 ANALYTICAL AND EXPERIMENTAL RESULTS, R = -1.0, r = 0.125 IN

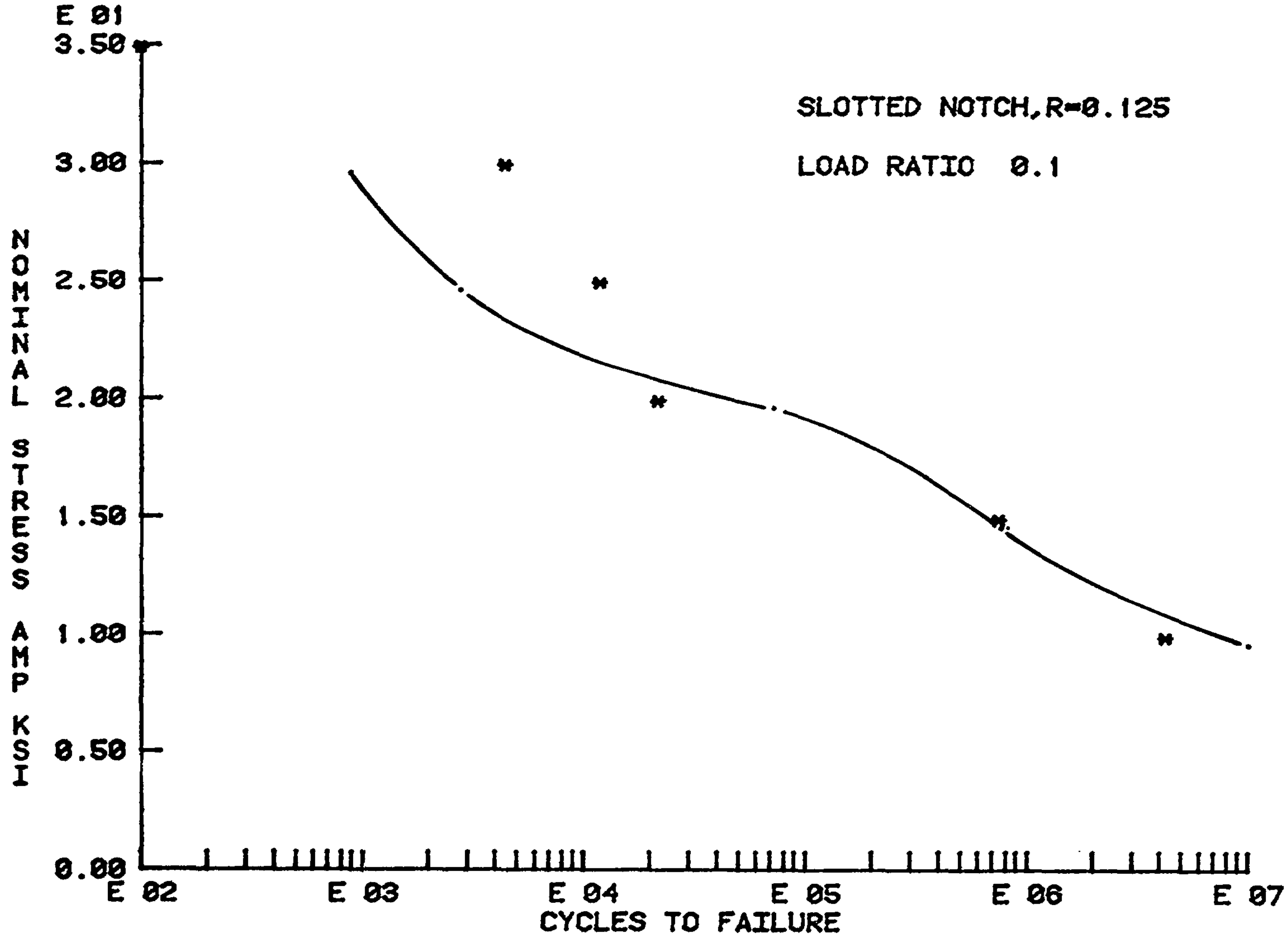


FIG. 9 ANALYTICAL AND EXPERIMENTAL RESULTS, R = 0.1, r = 0.125 IN

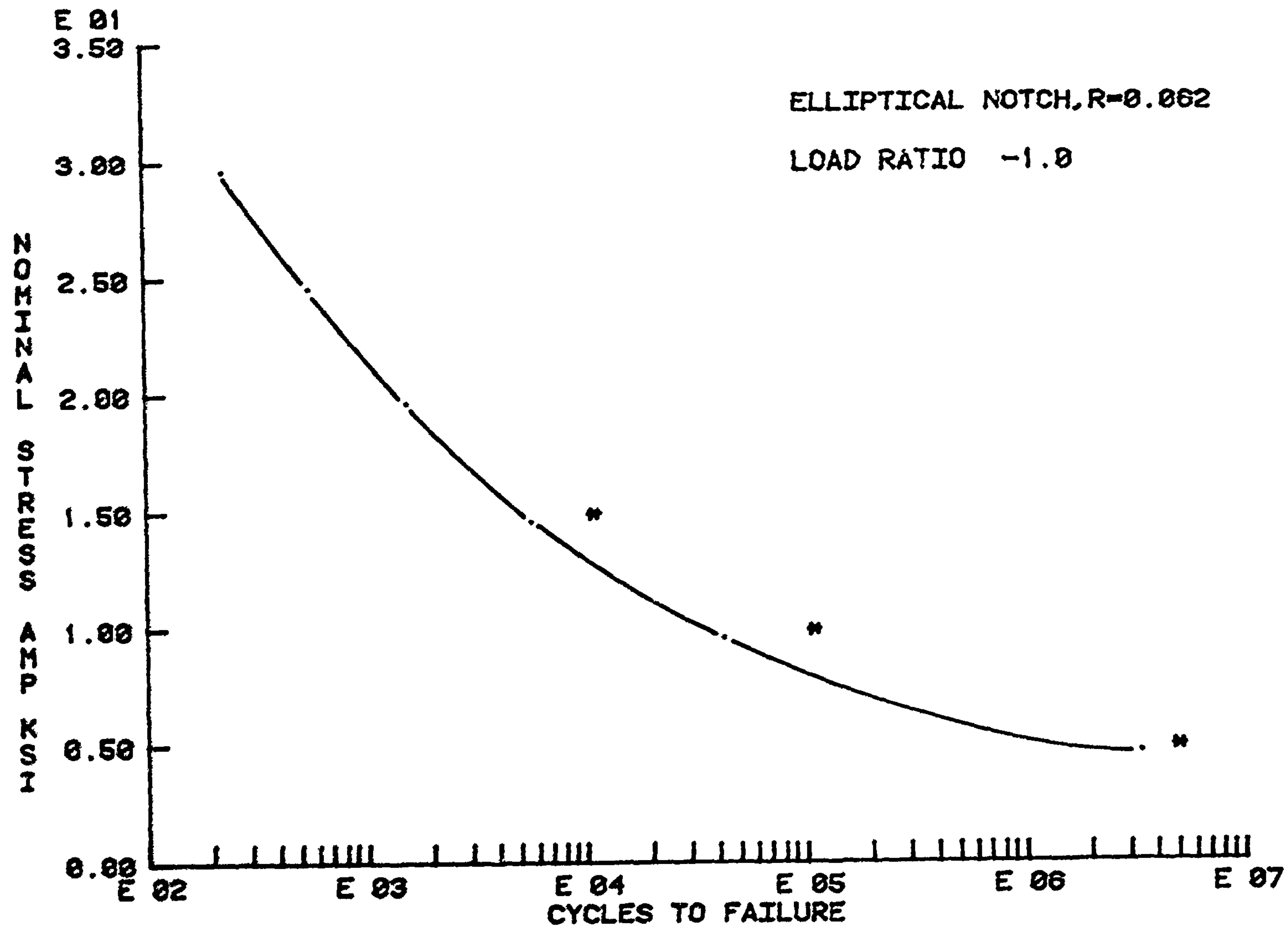


FIG. 10 ANALYTICAL AND EXPERIMENTAL RESULTS, R = -1.0, r = 0.062 IN

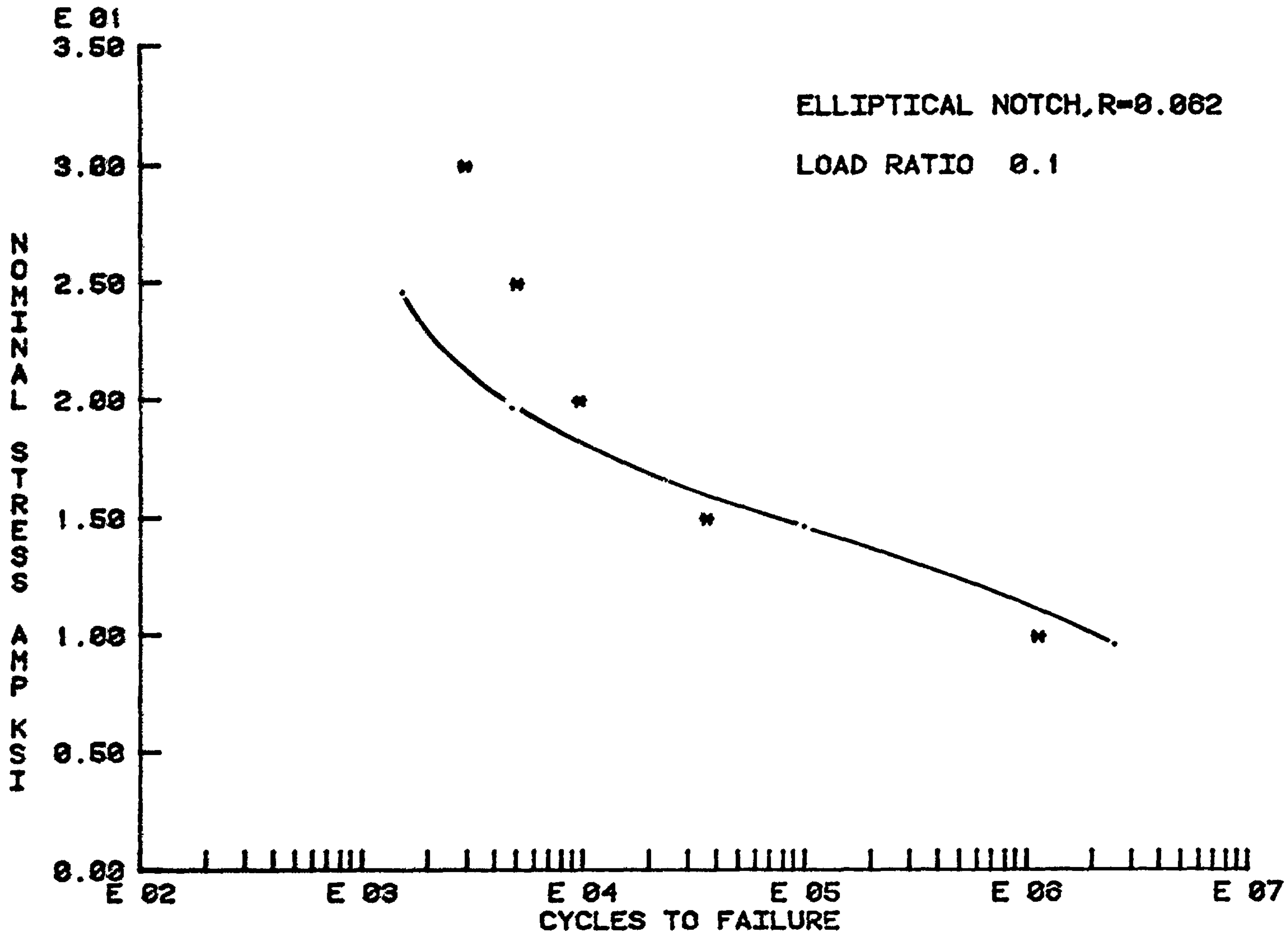


FIG. 11 ANALYTICAL AND EXPERIMENTAL RESULTS, R = 0.1, r = 0.062 IN

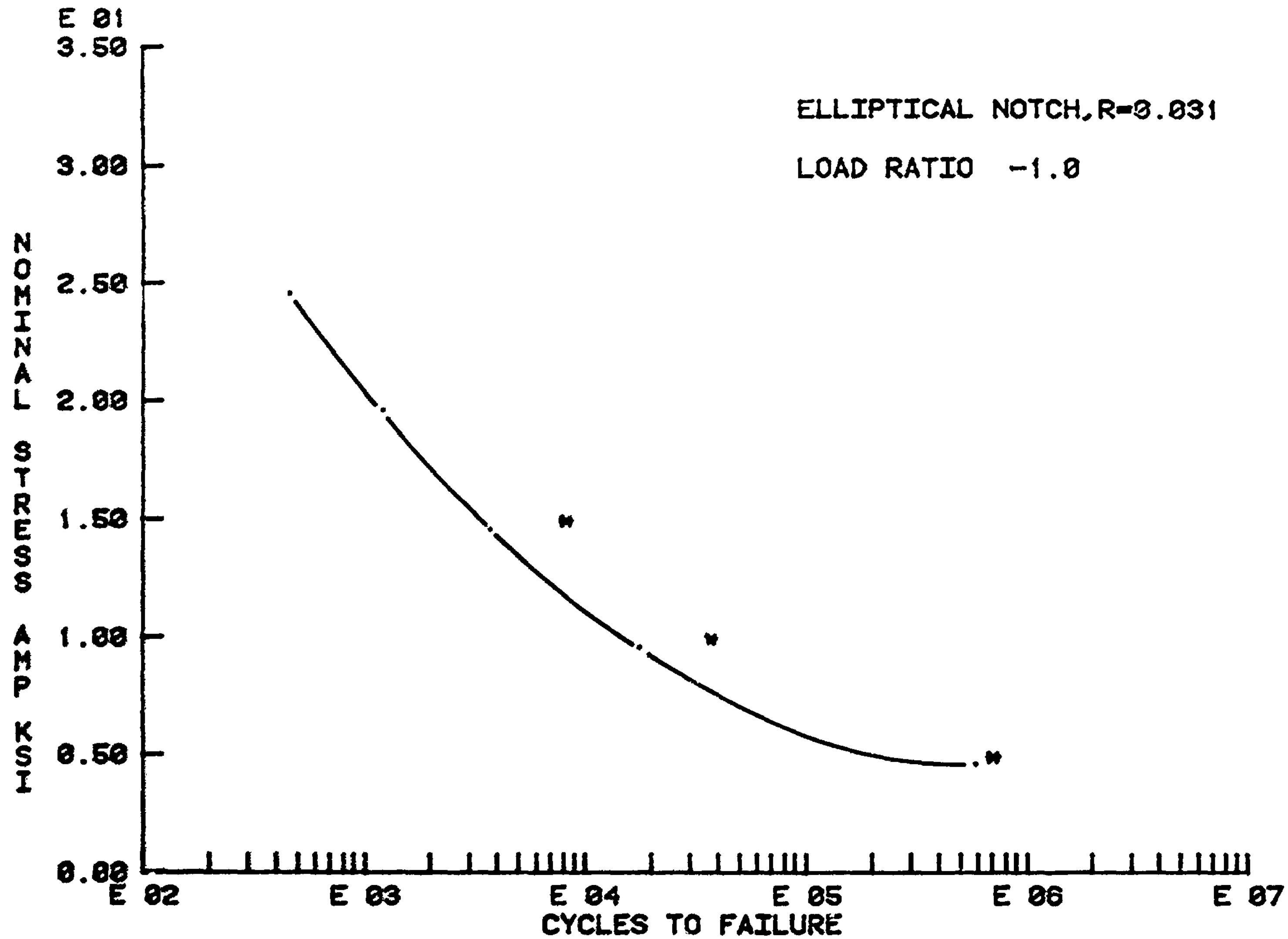


FIG. 12 ANALYTICAL AND EXPERIMENTAL RESULTS, R = -1.0, r = 0.031 IN

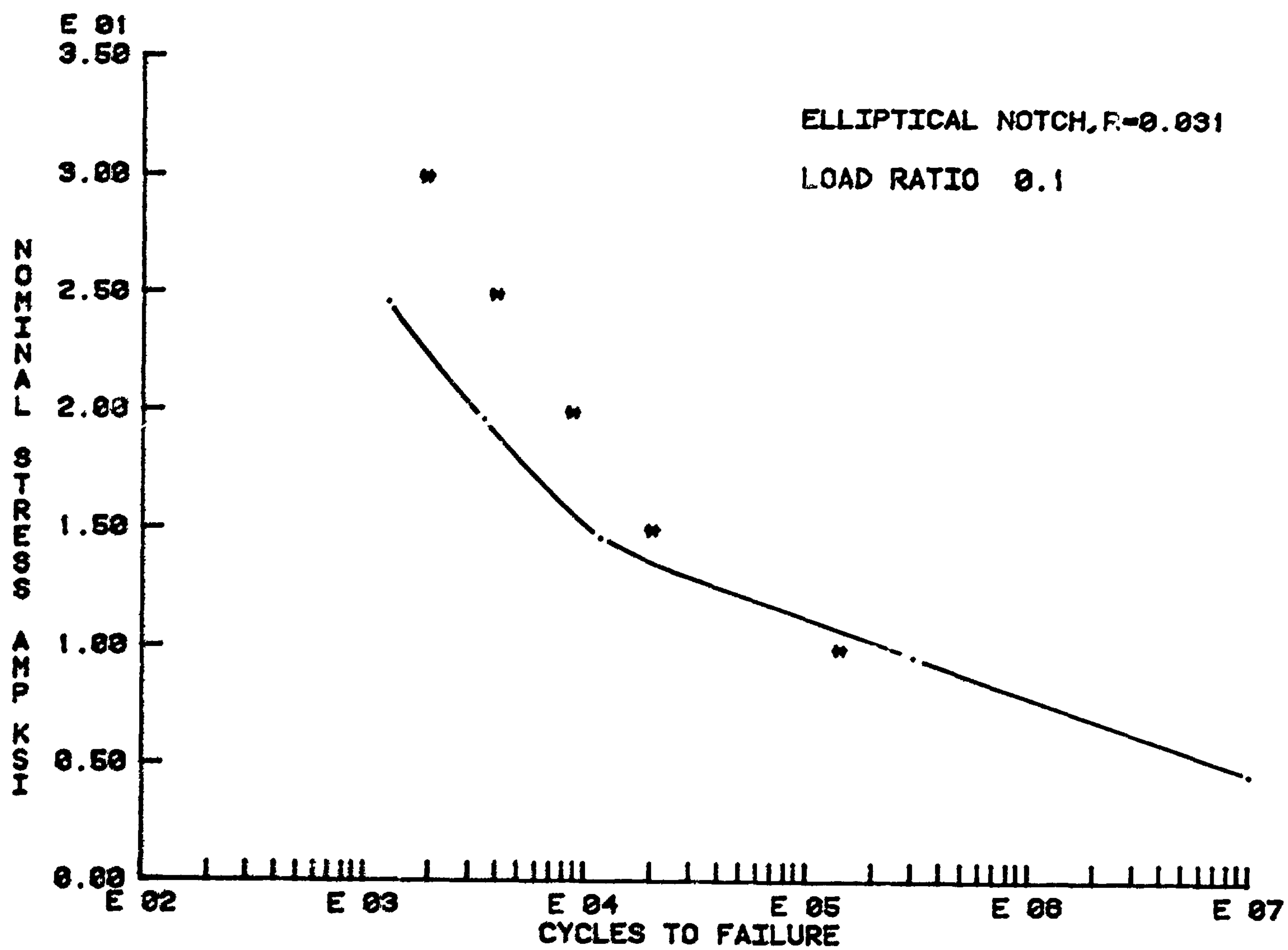


FIG. 13 ANALYTICAL AND EXPERIMENTAL RESULTS, R = 0.1, r = 0.031 IN

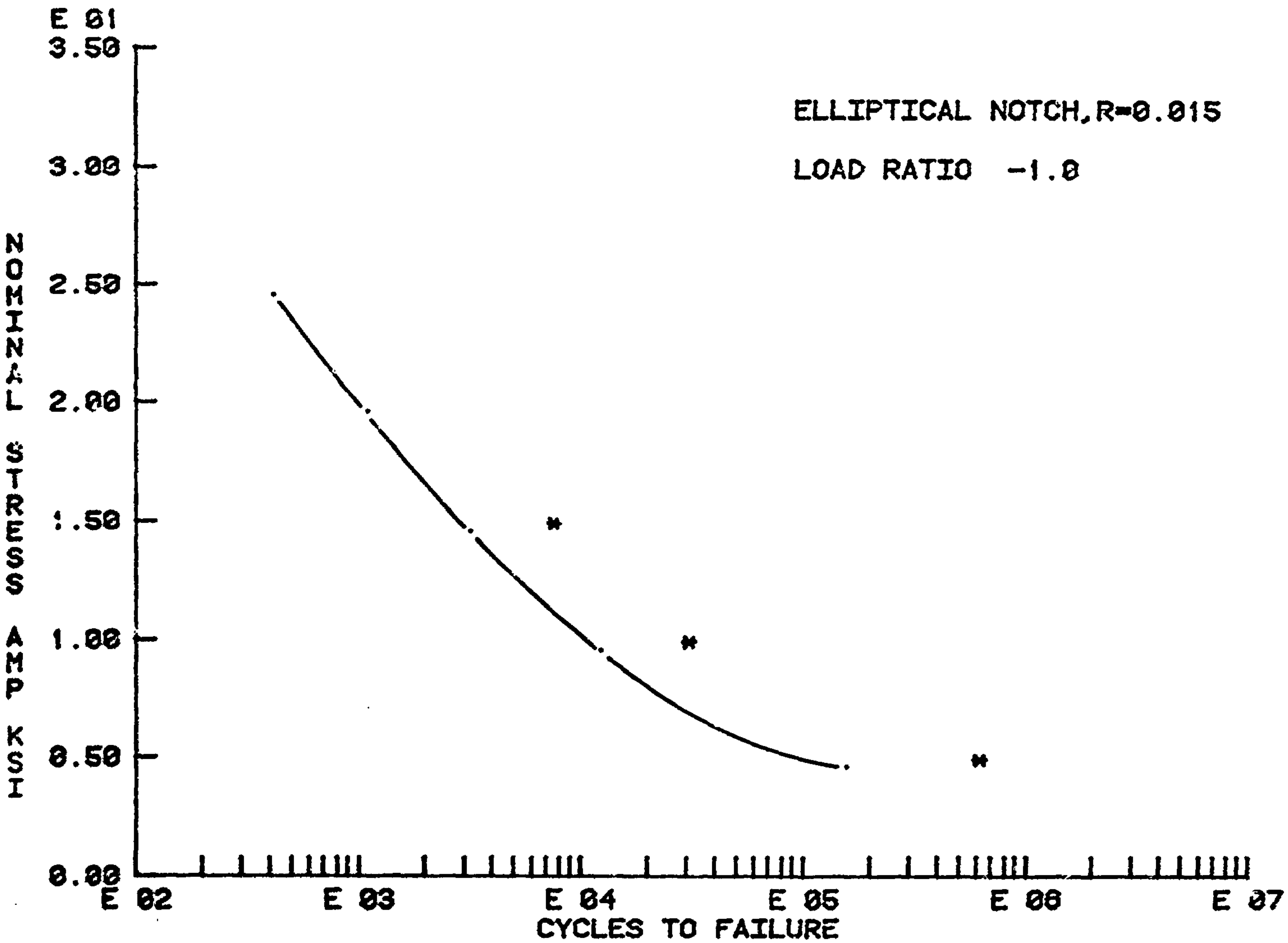


FIG. 14 ANALYTICAL AND EXPERIMENTAL RESULTS, R = -1.0, r = 0.015 IN

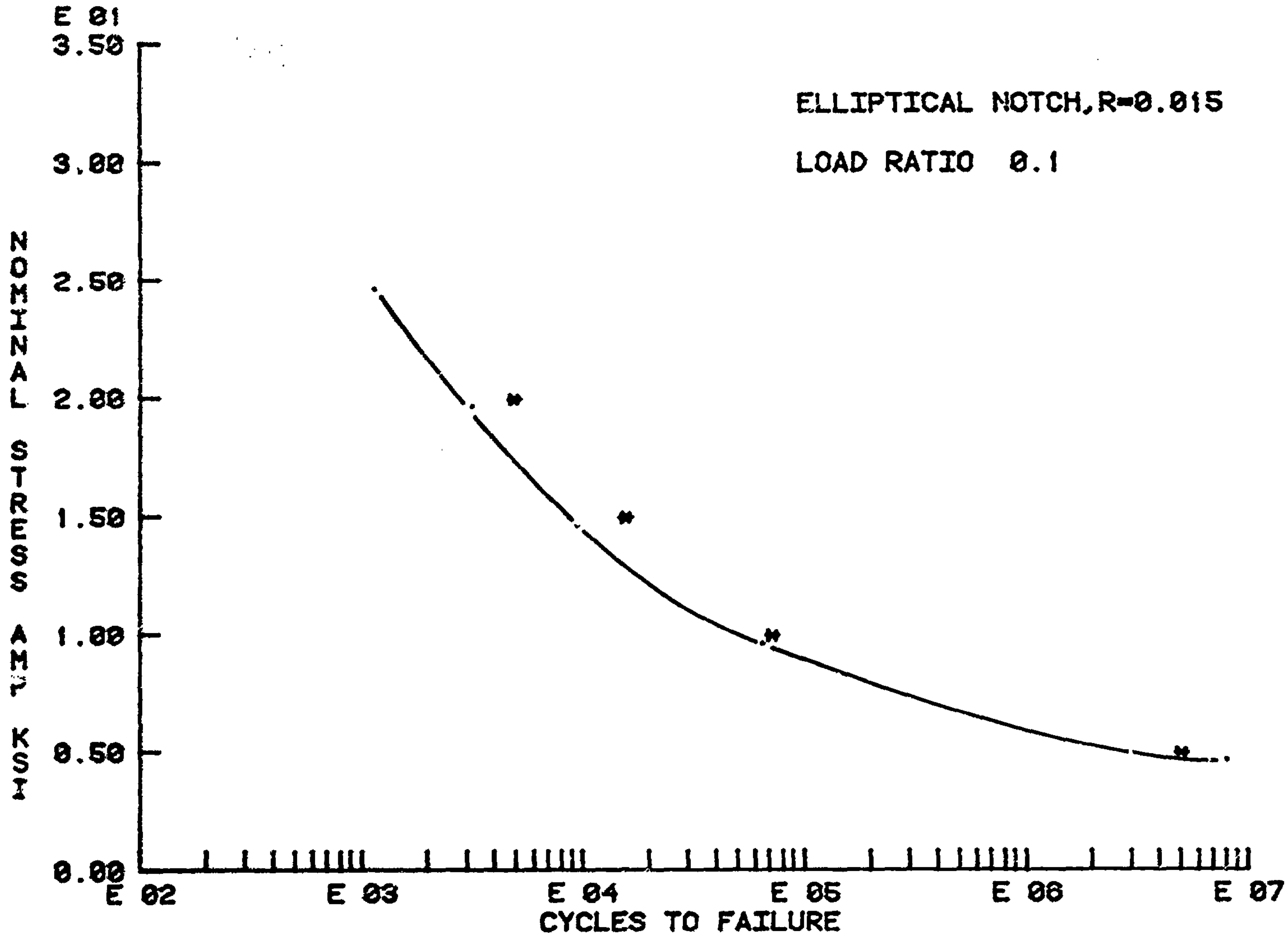


FIG. 15 ANALYTICAL AND EXPERIMENTAL RESULTS, R = 0.1, r = 0.015 IN

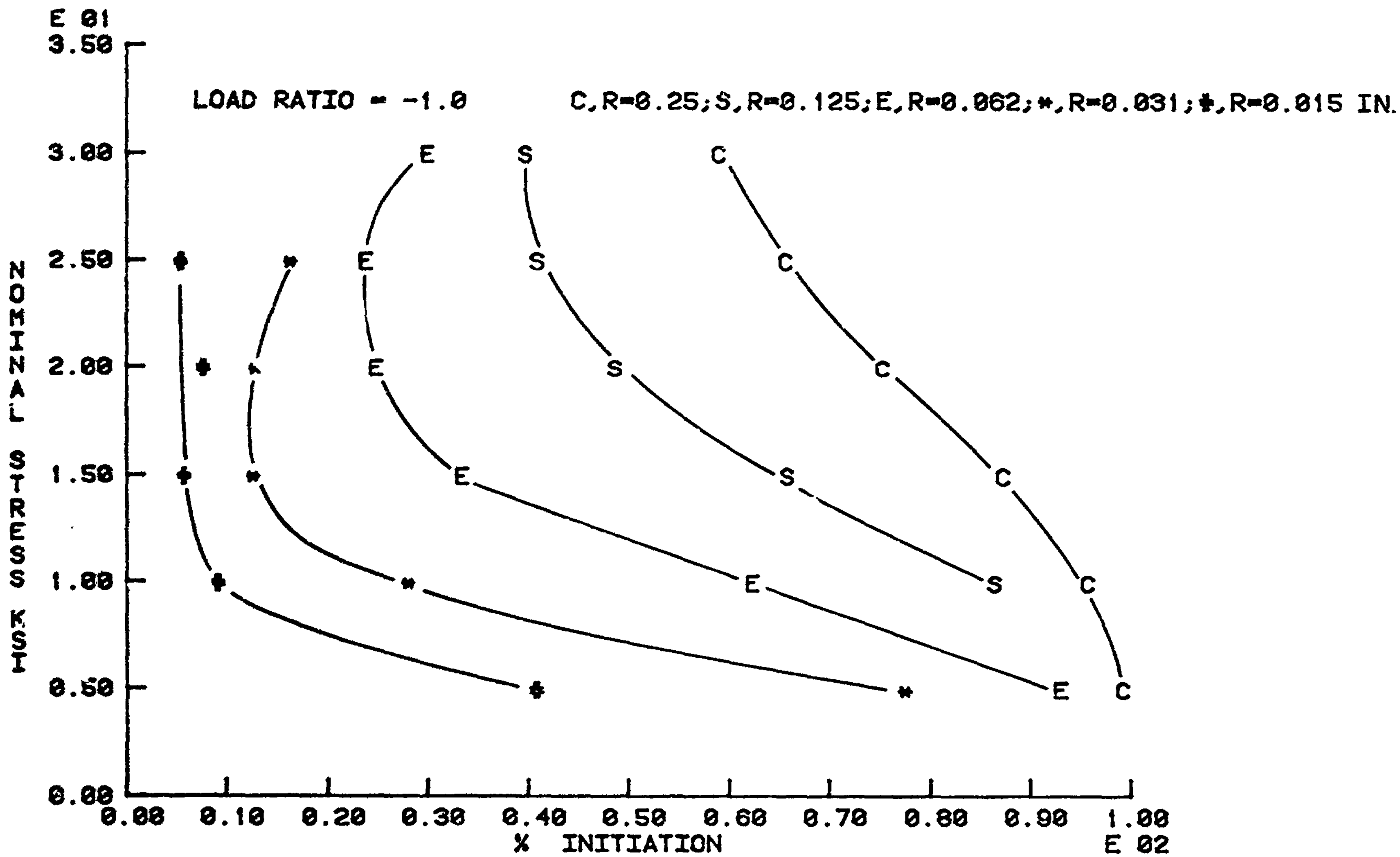


FIG. 16 CALCULATED % INITIATION VERSUS MAXIMUM NOMINAL STRESS, LOAD RATIO = -1.0

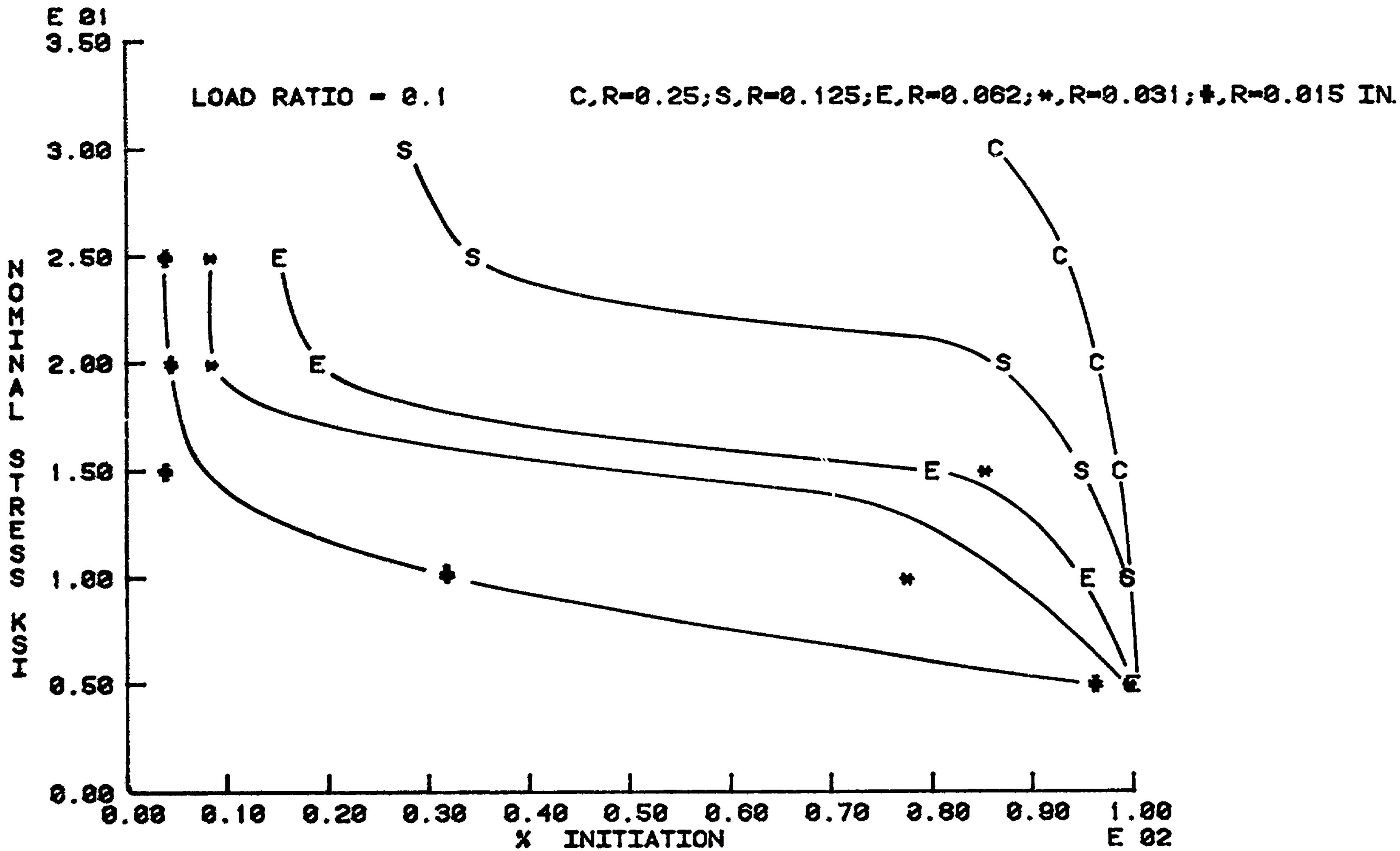


FIG. 17 CALCULATED % INITIATION VERSUS MAXIMUM NOMINAL STRESS, LOAD RATIO = 0.1

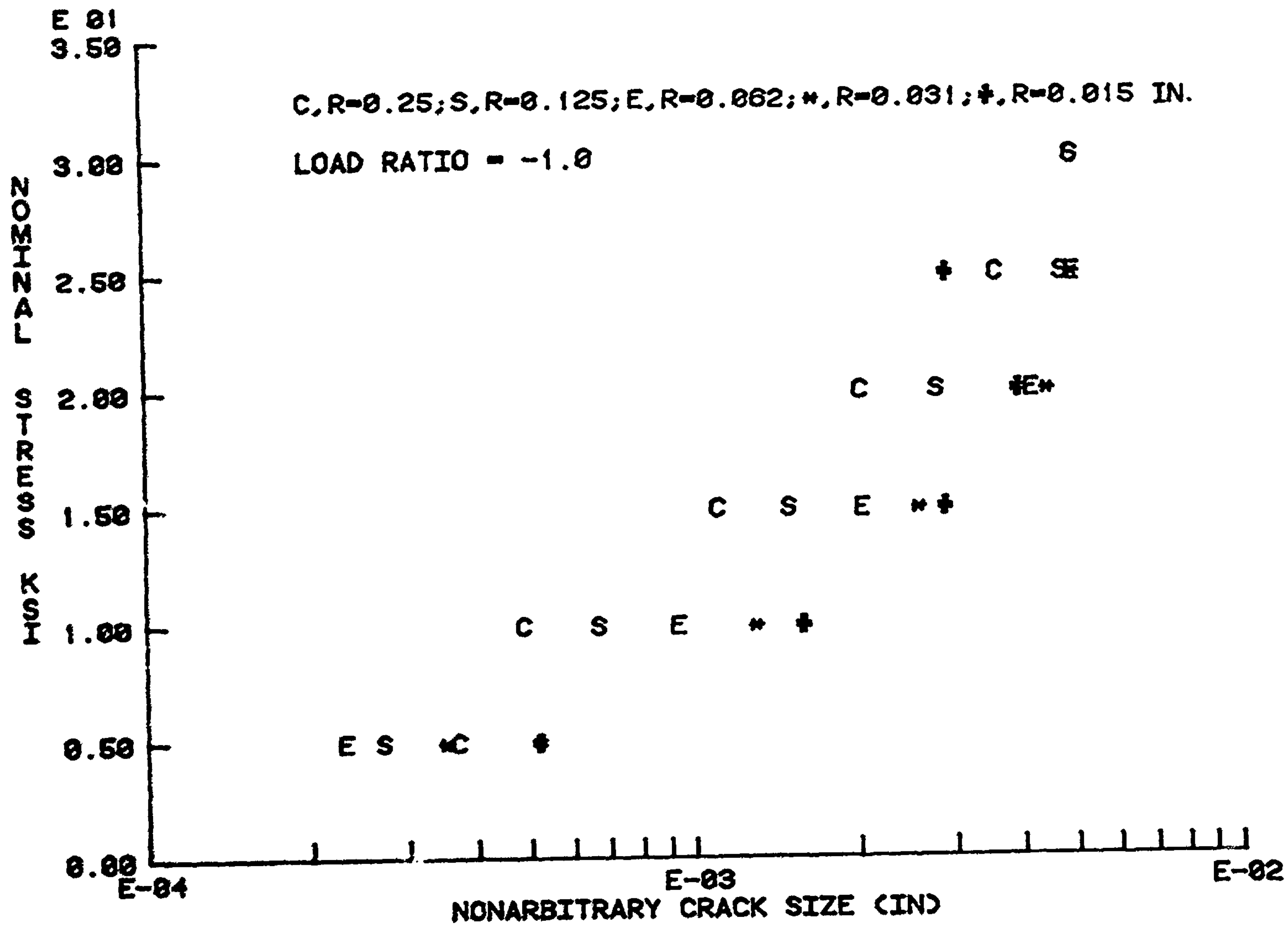


FIG. 18 NONARBITRARY CRACK SIZE VERSUS MAXIMUM NOMINAL STRESS, LOAD RATIO = -1.0

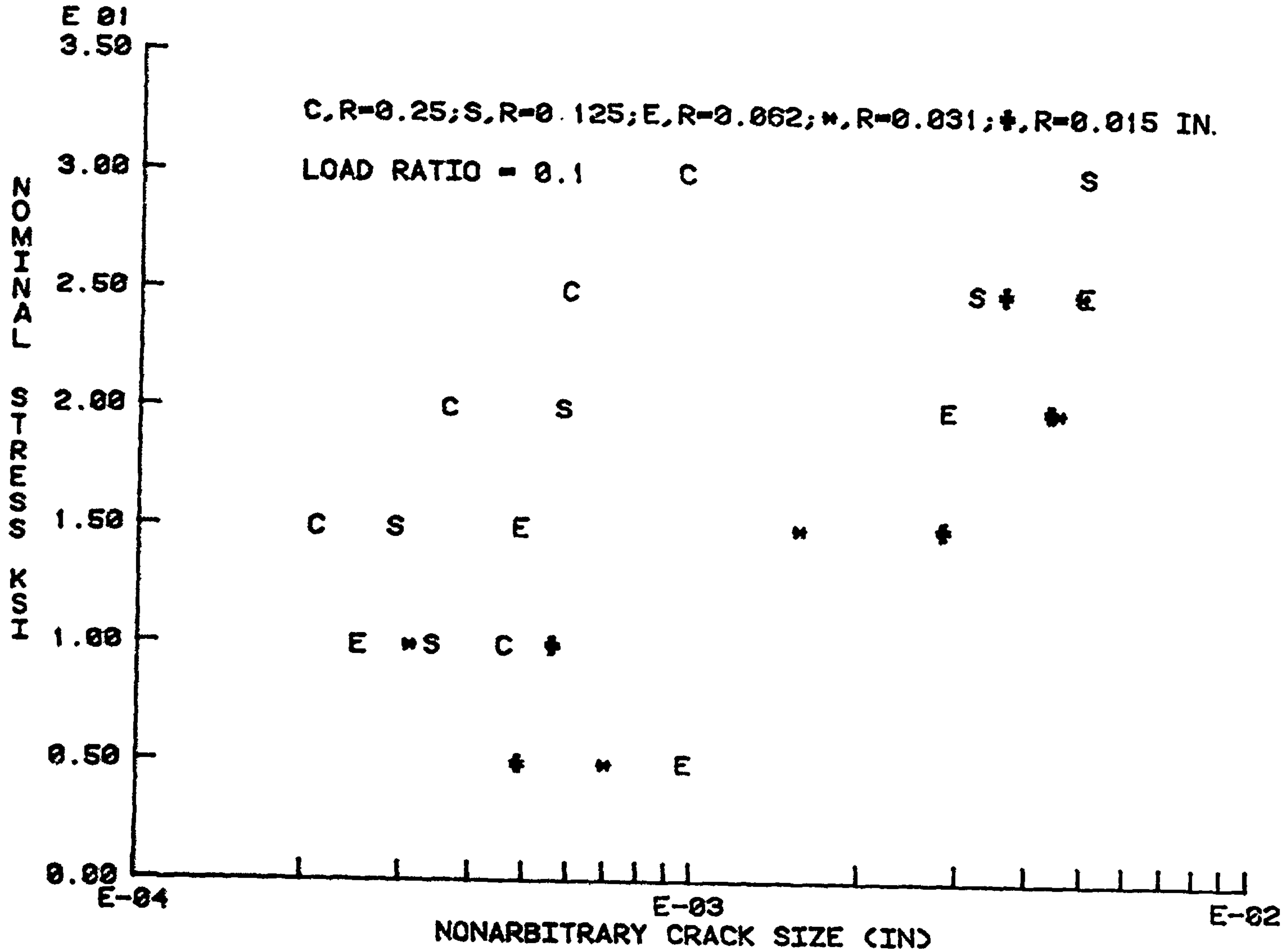


FIG. 19 NONARBITRARY CRACK SIZE VERSUS MAXIMUM NOMINAL STRESS, LOAD RATIO = 0.1

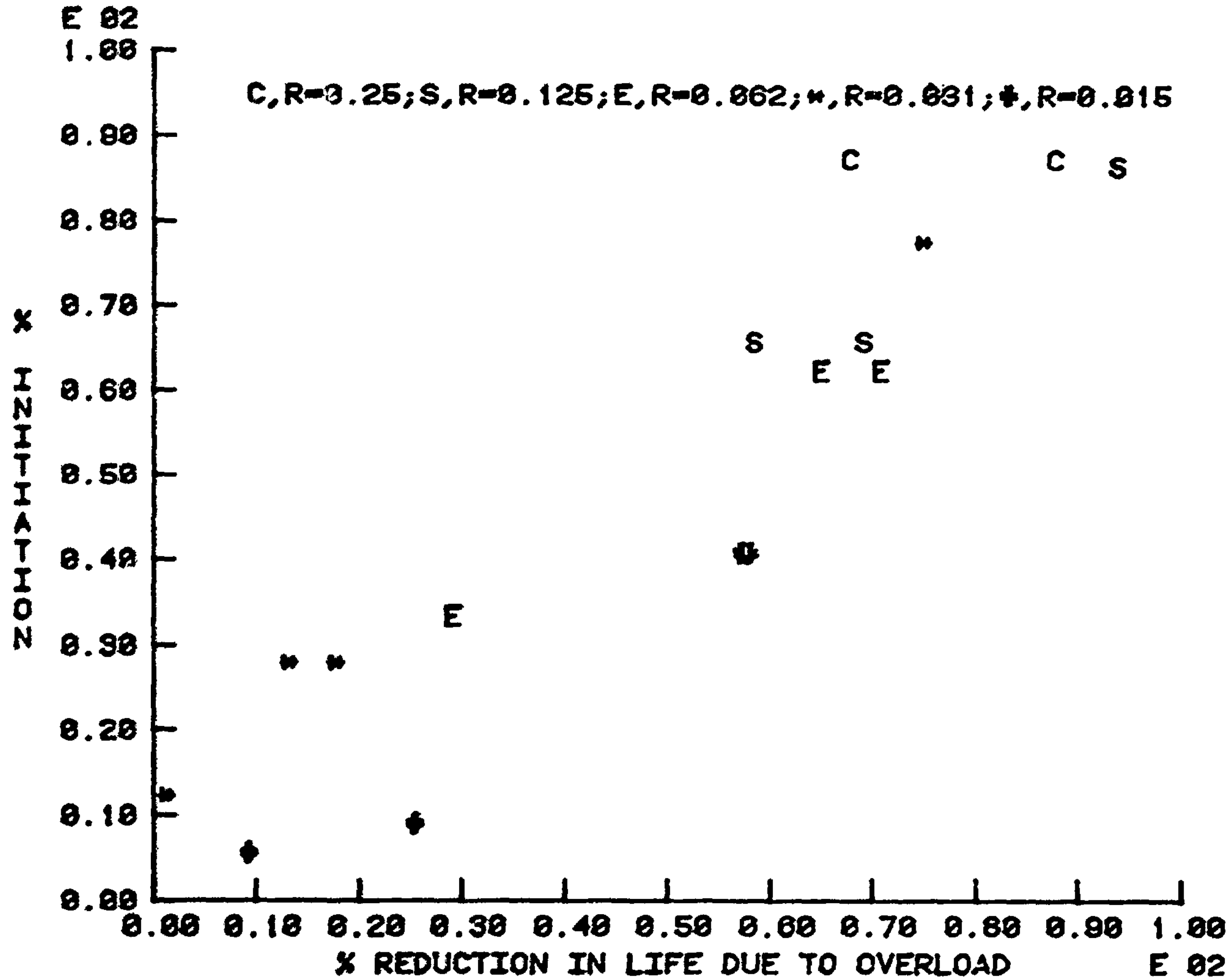


FIG. 20 CALCULATED % INITIATION VERSUS REDUCTION IN LIFE DUE TO AN INITIAL OVERLOAD

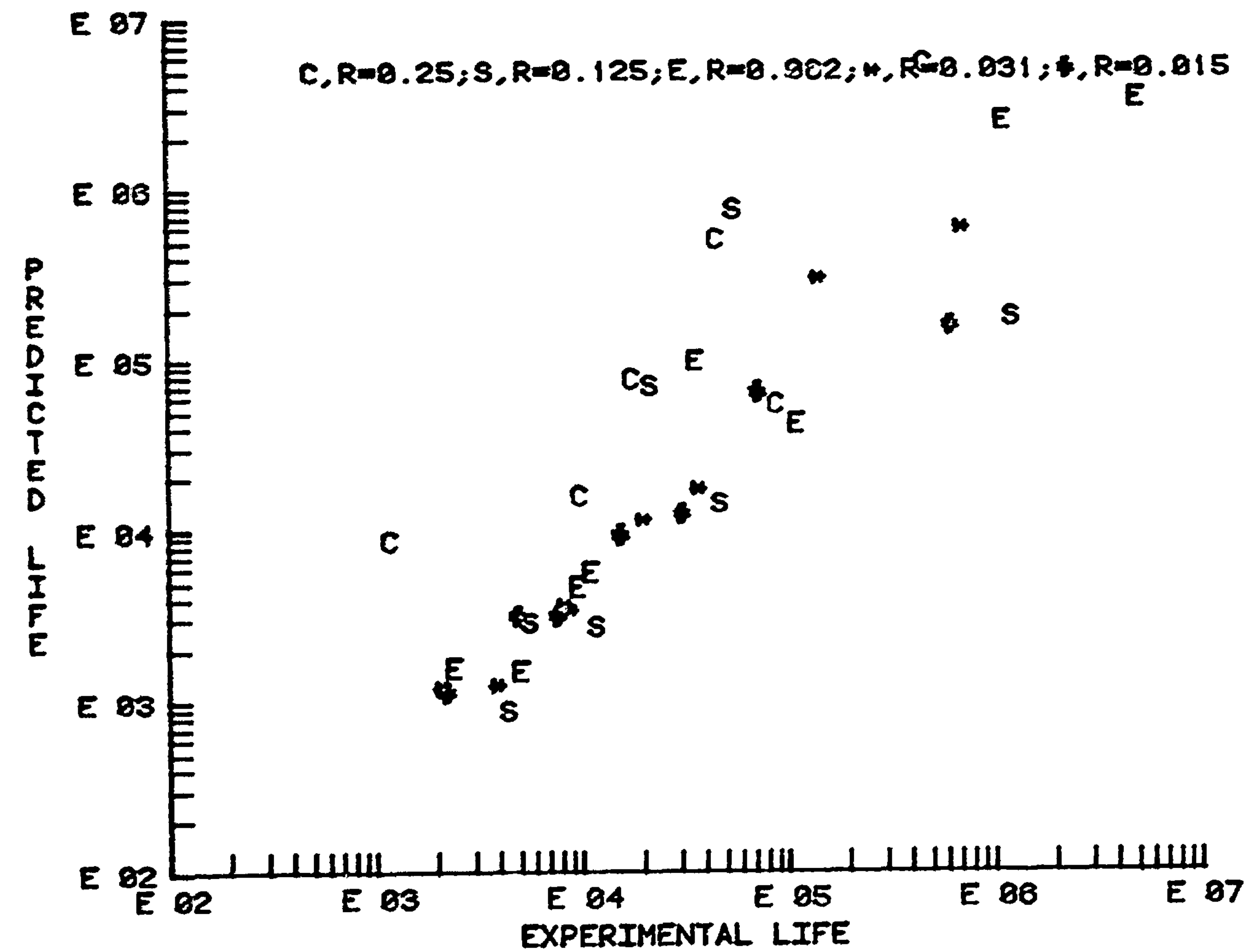


FIG. 21 EXPERIMENTAL VERSUS PREDICTED TOTAL LIVES TO FAILURE

*U.S. Government Printing Office: 1980 — 657-084/138